GROUNDWATER FLOW MODEL WORKING GROUP MEETING NO. 8

RED HILL BULK FUEL STORAGE FACILITY

February 12, 2018

Presenters:

Travis Hylton, USGS
Jeff Johnson, AECOM
Curt Stanley, GSI
Delwyn Oki, USGS
John Thackston, AECOM
Sorab Panday, GSI
Doug Roff, AECOM
Jack Kronen, AECOM
Tom Henderson, AECOM

FEBRUARY 12, 2018 AGENDA

0900-0905	Welcome/Introduction (Travis Hylton)
0905-0910	Navy Objectives and Working Group Intent (Curt Stanley)
0910-0920	Issues and Action Items (Curt Stanley)
0920-1020	Field Data Collection Update (Tom Henderson)
1020-1030	Break
1030-1130	Interim Modeling (Sorab Panday)
1130-1145	Synoptic Monitoring Update (Delwyn Oki)
1145-1200	Break to Summarize New Issues and Action Items
1200-1215	Summary and Next Steps (Jeff Johnson, Curt Stanley)
	Upcoming Working Group Meetings (Travis Hylton, Tracy Saguibo)
	Next Meeting – March 16, 2018

NAVY'S MODELING OBJECTIVES

- The objective of groundwater modeling is to help ascertain potential risk to water supply wells as a result of a potential range of releases from the Red Hill Bulk Fuel Storage Facility under a range of reasonable pumping conditions within the model domain.
- The results of this modeling effort will then be used to:
  1. Inform decisions related to the Tank Upgrade Alternatives (TUA)
  2. Inform decisions related to potential remedial alternatives

GROUNDWATER FLOW MODELING WORKING GROUP INTENT

- **The intent of the GWFM Working Group is to support the Navy's objectives relative to developing timely and technically defensible groundwater flow and contaminant fate & transport (CF&T) models for Red Hill.**
  - **Technical feedback from Subject Matter Experts (SMEs) for consideration by the Navy on key elements of model development**
  - **Provide assistance in ensuring that all appropriate data are considered in development of the model**
  - **Provide assistance in collecting relevant data**

* The GWFM Working Group focus is on the deep technical issues related to technically defensible model development

REVIEW OF ISSUES AND ACTION ITEMS

- **Refer to formal response**

DATA REQUESTS

- DLNR water use permit(s) across model domain
- Sampling data from BWS well BWS2253-J1 near Tank 405
- Halawa Deep shallow monitor tube data
- BWS data from Watercress Farms pumping to quarry
- Navy working on data requests from BWS and Regulatory Agencies

FIELD DATA COLLECTION UPDATE

- **RHMW11 wellhead survey update**
- **Seismic survey update**

GROUNDWATER MODELING

- **Action items from previous meetings**
  - Springs (Kalauao Springs and Pearl Harbor at Kalauao)
    - Dimensions
    - Drain elevations
- **Calibration**
  - Final values selected from interim model calibration
  - Metrics
  - Water balances compared to conceptual balances
- **Particle tracking with layers indicated**
- **Interim Modeling Sensitivity Analysis (for calibration and particle tracking)**

STEADY-STATE MODEL PUMPING DATA

Well Name	Well ID	Annual Average Pumpage (MGD)		
		2006	2015	2017
Kalihi Shaft	2052-08	8.12	8.39	5.68
Kalihi	2053-08	0	0	0
Fort Shafter	2053-11	0.5	0.49	0.52
Hickam AF Base	2057-04	0	0	0
Moanalua	2153-02	0.03	0.03	0.02
Moanalua Deep	2153-05	1.27	1.27	1.27
TAMC 1	2153-07	0.36	0.48	0.41
Moanalua 1	2153-10	3.54	1.5	1.28
Moanalua 2	2153-11	0	0	0
Moanalua 3	2153-12	0	0	0
HNL Intl CC	2154-01	0.45	0.47	0.66
Kalihi Aerator	2250-01	0	0	0
Navy Halawa	2255-32	0.34	0.34	0.34
Halawa 2	2255-37	0.82	1.12	0.83
Halawa 3	2255-38	0	0	0
Halawa 1	2255-39	0	0	0
'Aiea Gulch 1	2355-03	0.77	0.74	0.73
'Aiea Gulch 2	2355-05	0	0	0
'Aiea 1	2355-06	1.01	0.23	0.92
'Aiea 2	2355-07	0	0	0

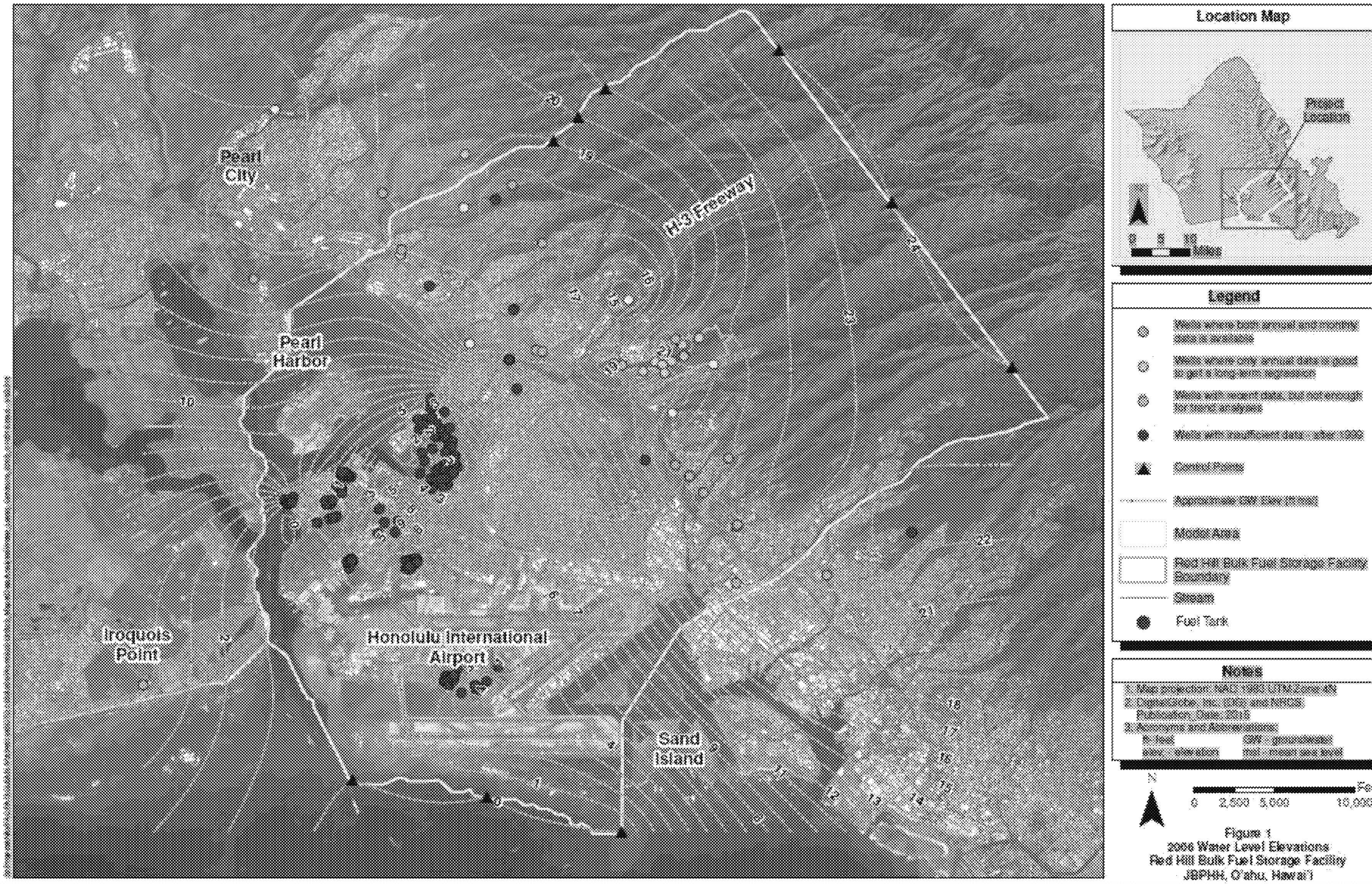
STEADY-STATE MODEL PUMPING DATA

Well Name	Well ID	Annual Average Pumpage (MGD)		
		2006	2015	2017
Kalauao P1	2355-09	7.58	8.5	4.95
Kalauao P4	2355-10	0	0	0
Kalauao P2	2355-11	0	0	0
Kalauao P3	2355-12	0	0	0
Kalauao P5	2355-13	0	0	0
Kalauao P6	2355-14	0	0	0
WG Minami 2007	2355-16	0.00045	0.00045	0.00045
Waimalu I-1	2356-49	0	0	0
Waimalu I-2	2356-50	0	0	0
Pearl CC	2356-54	0.28	0.42	0.23
Kaonohi I-2	2356-55	1.07	0.84	0.78
Kaonohi I-1	2356-56	0	0	0
Ka'amilo 1	2356-58	1.82	0	0
Ka'amilo 2	2356-59	0	0	0
Waimalu II-1	2356-60	0	0	0
Kaonohi II-1	2356-61	0	0	0
Kaonohi II-2	2356-62	0	0	0
Waimalu II-2	2356-63	0	0	0
Waimalu II-3	2356-64	0	0	0
Kaonohi II-3	2356-65	0	0	0

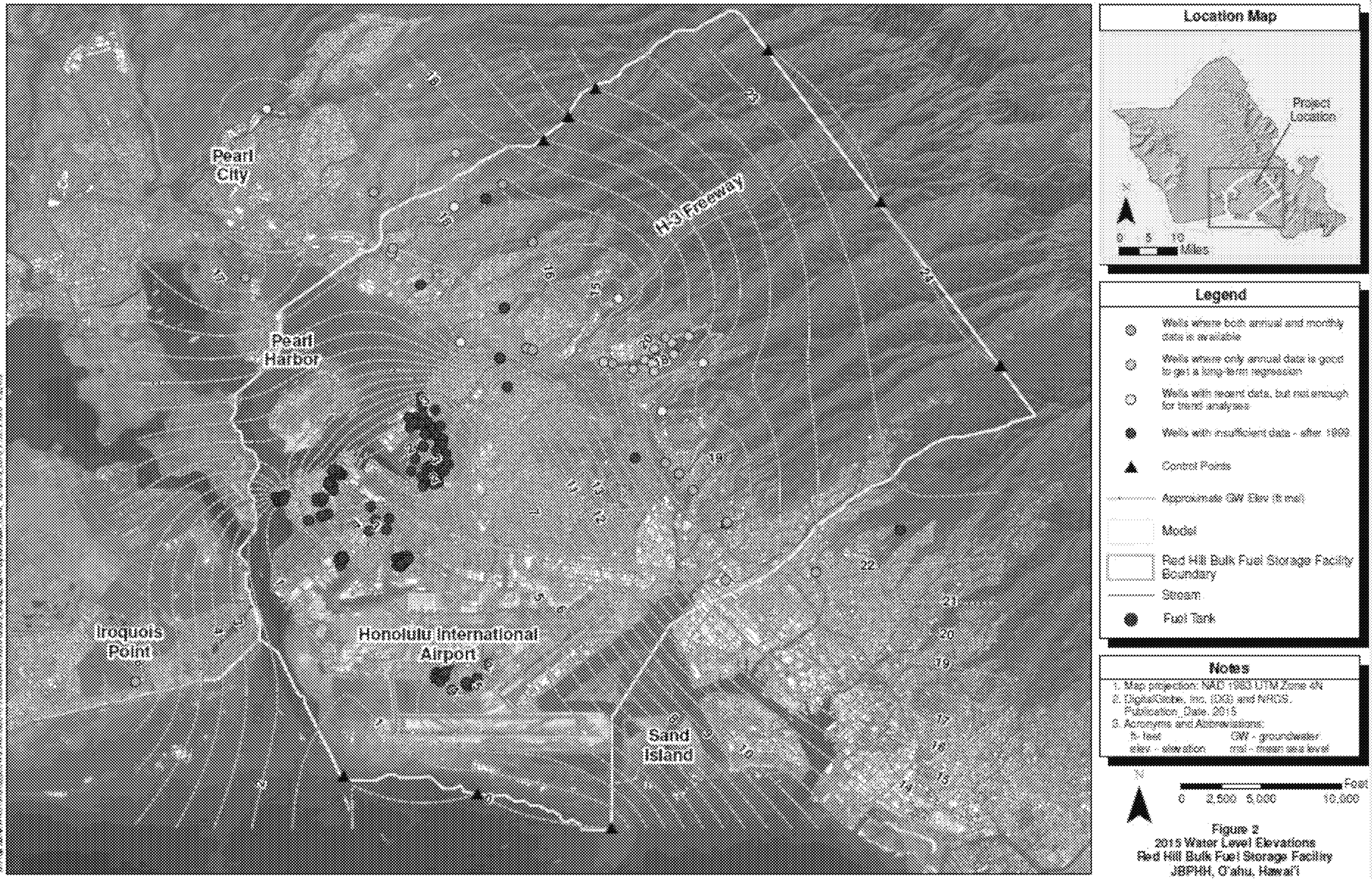
STEADY-STATE MODEL PUMPING DATA

Well Name	Well ID	Annual Average Pumpage (MGD)		
		2006	2015	2017
Lau Farm	2356-70	1.4	1.4	1.4
Waiau	2357-08	0	0	0
Kaahumanu I-2	2357-23	1.12	0.92	0.44
Kaahumanu I-1	2357-24	0	0	0
Waimalu	2455-02	0.0023	0	0.0023
Waimalu	2455-03	0.00052	0.00032	0.00032
Newtown 1	2456-01	0.62	2.13	0.79
Newtown 2	2456-02	0	0	0
Newtown 3	2456-03	0	0	0
Red Hill Shaft	2254-01	2.87	4.15	3.76
Halawa Shaft	2354-01	12.16	5.91	8.06

REVISED WATER LEVEL CONTOURS 2006 (W/O CONTROL POINT NEAR H-3)



REVISED WATER LEVEL CONTOURS 2015 (W/O CONTROL POINT NEAR H-3)



REVISED WATER LEVEL CONTOURS 2017 (W/O CONTROL POINT NEAR H-3)

UPDATED KALAUAO SPRINGS (WATERCRESS FARM) DRAIN AREA IN LAYER 2

MODEL CALIBRATION

CALIBRATION SUMMARY

- **Steady-state average conditions for 2006, 2015, and 2017**
  - Evaluate model-wide water level statistics (ME, AME, RMS, scatterplots, regression coefficient) and spring-flow errors
  - Evaluate focus area water level statistics (ME, AME, RMS, scatterplots, regression coefficient) and spring-flow errors
  - Evaluate water level contours against conceptual model for flow
  - Evaluate water budget terms against conceptual model water budgets
  - Evaluate spatial bias
  - Evaluate key head differences
- **Transient synoptic studies of 2006 and 2015**
  - Visual evaluation of water level changes
- **Evaluate cause and impact of significant errors**

MODEL CALIBRATION METHODS

- **Interactive expert calibration**
  - Evaluate sensitivities and understand dynamics
  - Perform rough calibration
- **Automatic calibration with PEST**
  - Fine-tune calibration
  - Explore impact of different calibration target sets
  - Explore significance of various parameters

INTERIM MODEL PARAMETERS

Material	Kh ft/day	Kv ft/day	L:T Anisotropy
Caprock (layer 1)	1208	0.08	1
Valley fill (layer 1)	100	1	1
Saprolite (layer 2)	0.1	0.01	1
Saprolite (layer 3)	10	1	1
Basalt (layers 2, 3, 4, 5)	2000	20	0.33

Other Parameters

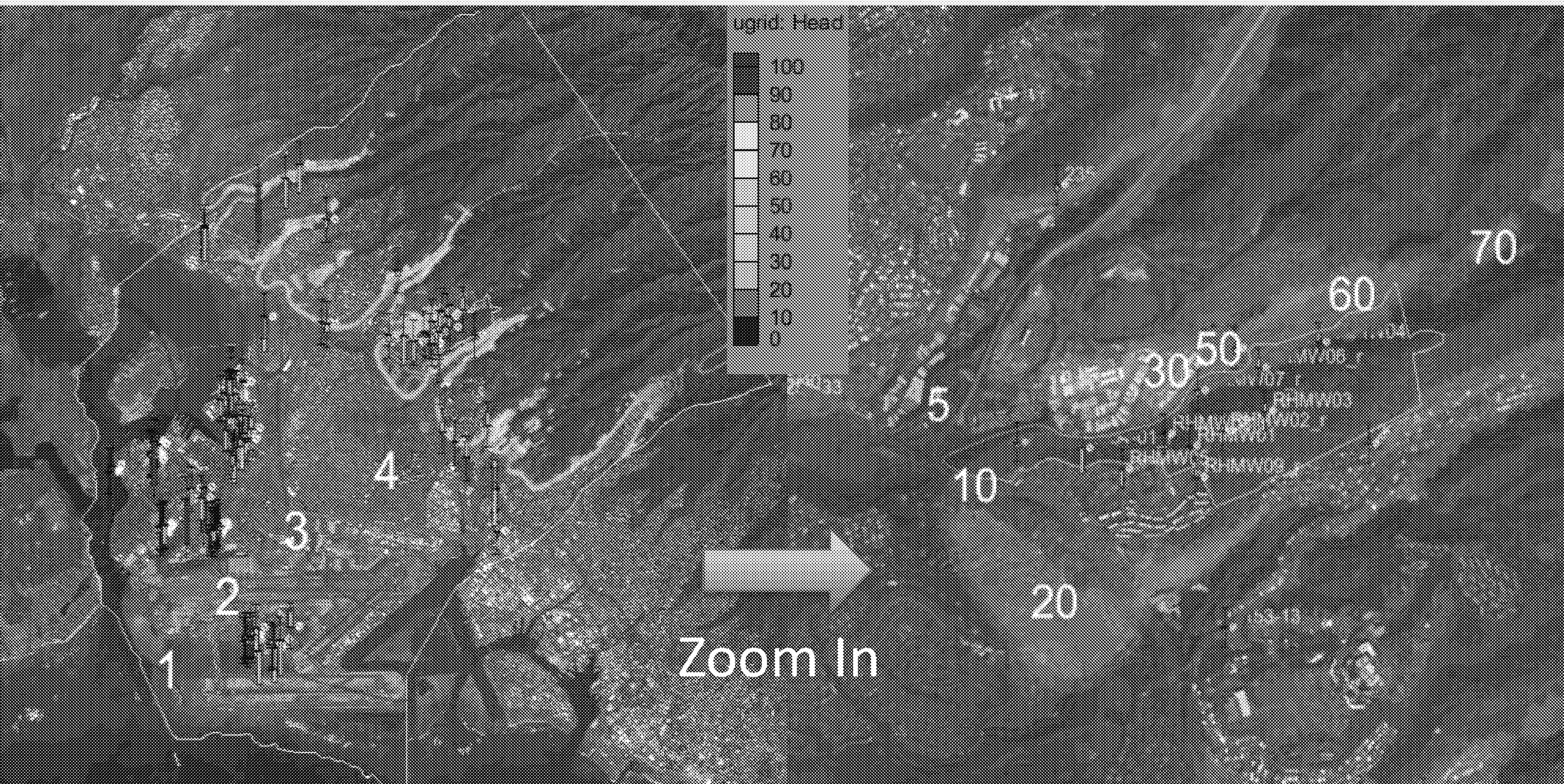
Recharge Multiplier	1.27 (2006)	0.95 (2015)	0.97 (2017)
GHB Conductance, ft^2/day	3,416 (Pearl Harbor Bay)	1,242 (South)	10^{-7} to 10^{-6} (NW/SE)
Drain Conductance, ft^2/day	1E6 (Pearl Harbor Spring at Kalauao)	5,000 (Kalauao Spring)	10 ft msl (elevation)

INTERIM MODEL PARAMETERS

Recharge Multiplier			
Year	2006	2015	2017
Multiplier	1.27	0.95	0.97

Location	GHB Conductance
Pearl Harbor	3,416 $feet^2$/day
South Open Water	1,242 $feet^2$/day
NW & SE	$10^{-7} – 10^{-6}$/day
Location	DRN Conductance
Pearl Harbor Spring at Kalauao	2,000,000 $feet^2$/day
Kalauao Spring	5,000 $feet^2$/day
Drain Elevation	+10 feet msl

SIMULATED 2017 GROUNDWATER CONTOURS LAYER 1



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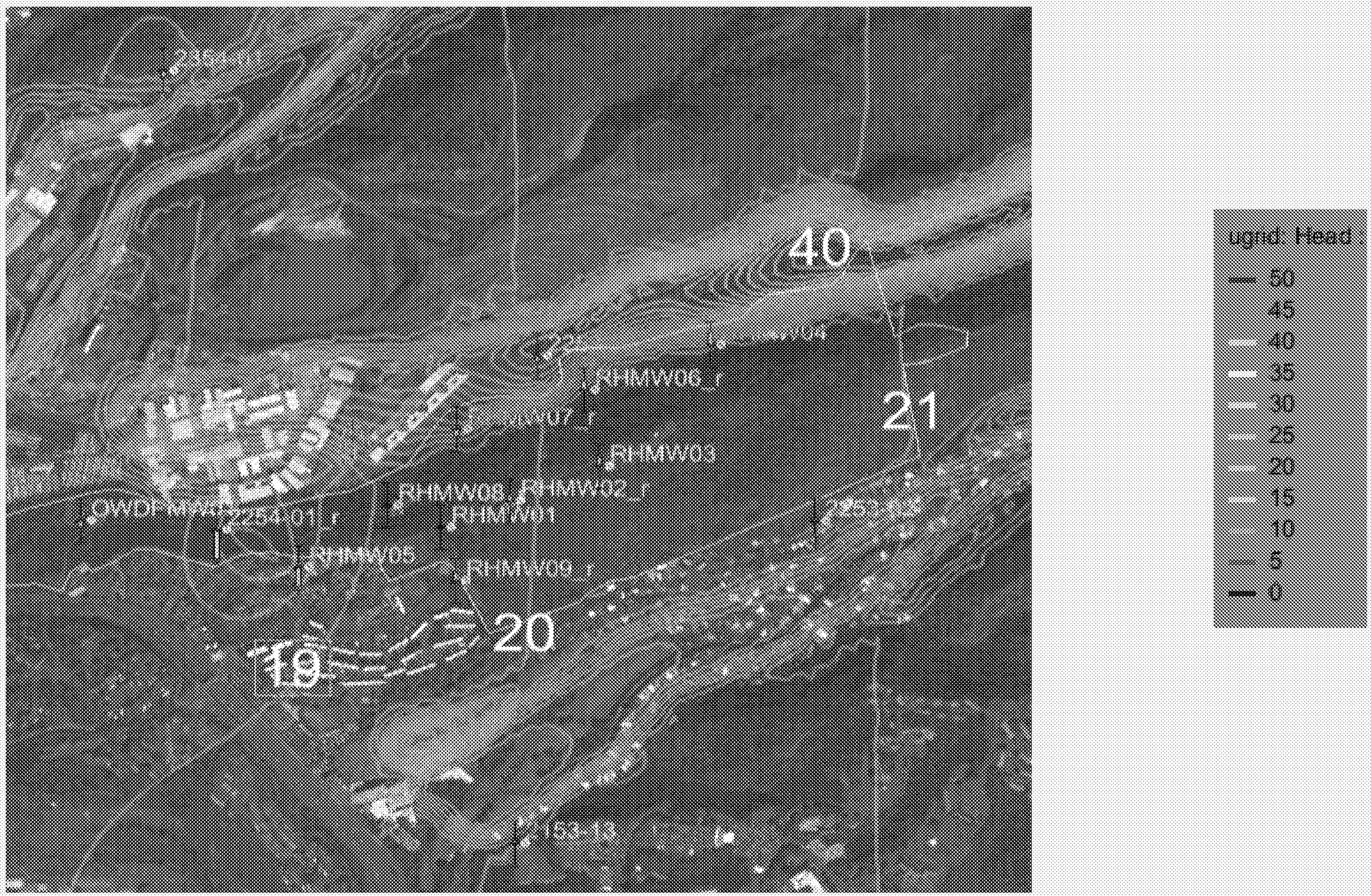
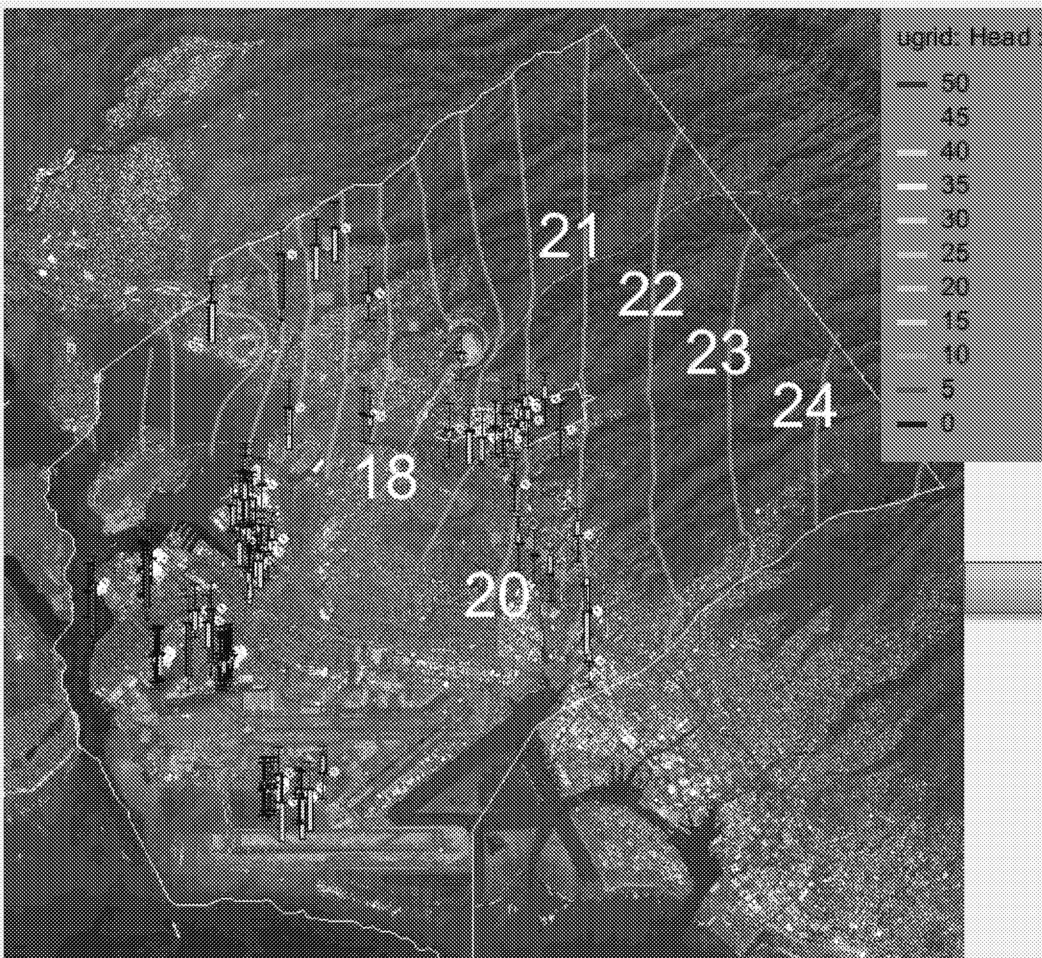
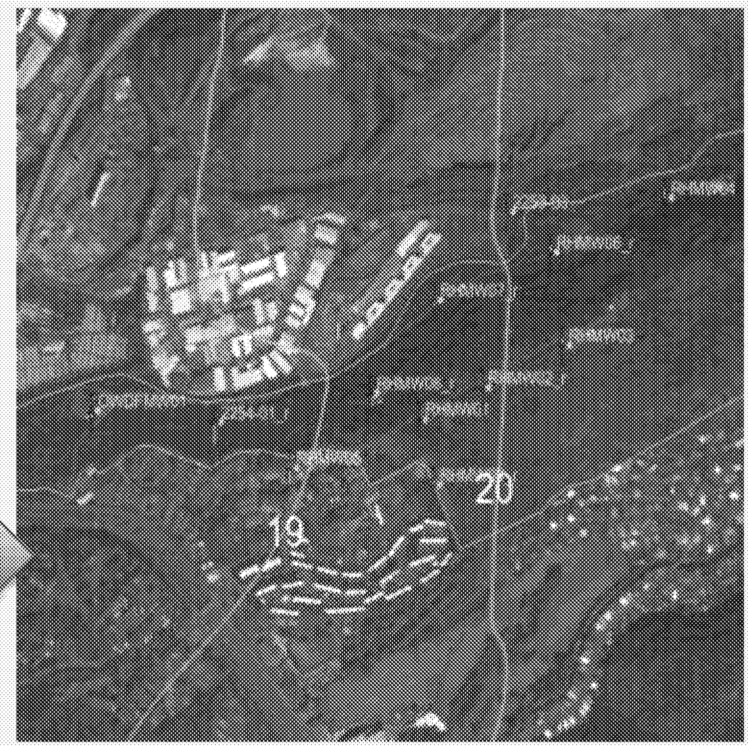
SIMULATED 2017 GROUNDWATER CONTOURS
LAYER 2

SIMULATED 2017 GROUNDWATER CONTOURS LAYER 2 ZOOMED IN



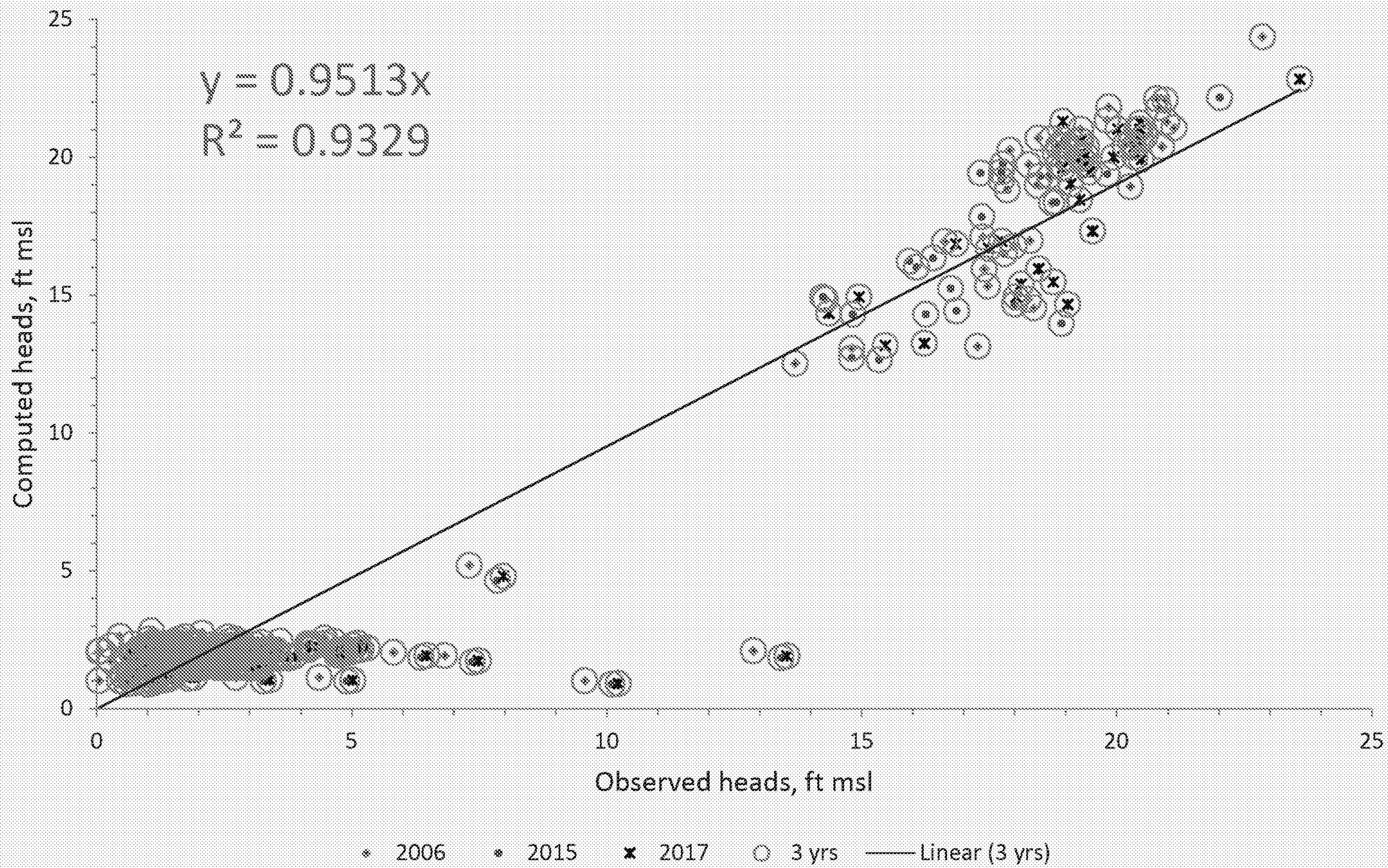
SIMULATED 2017 GROUNDWATER CONTOURS LAYER 3





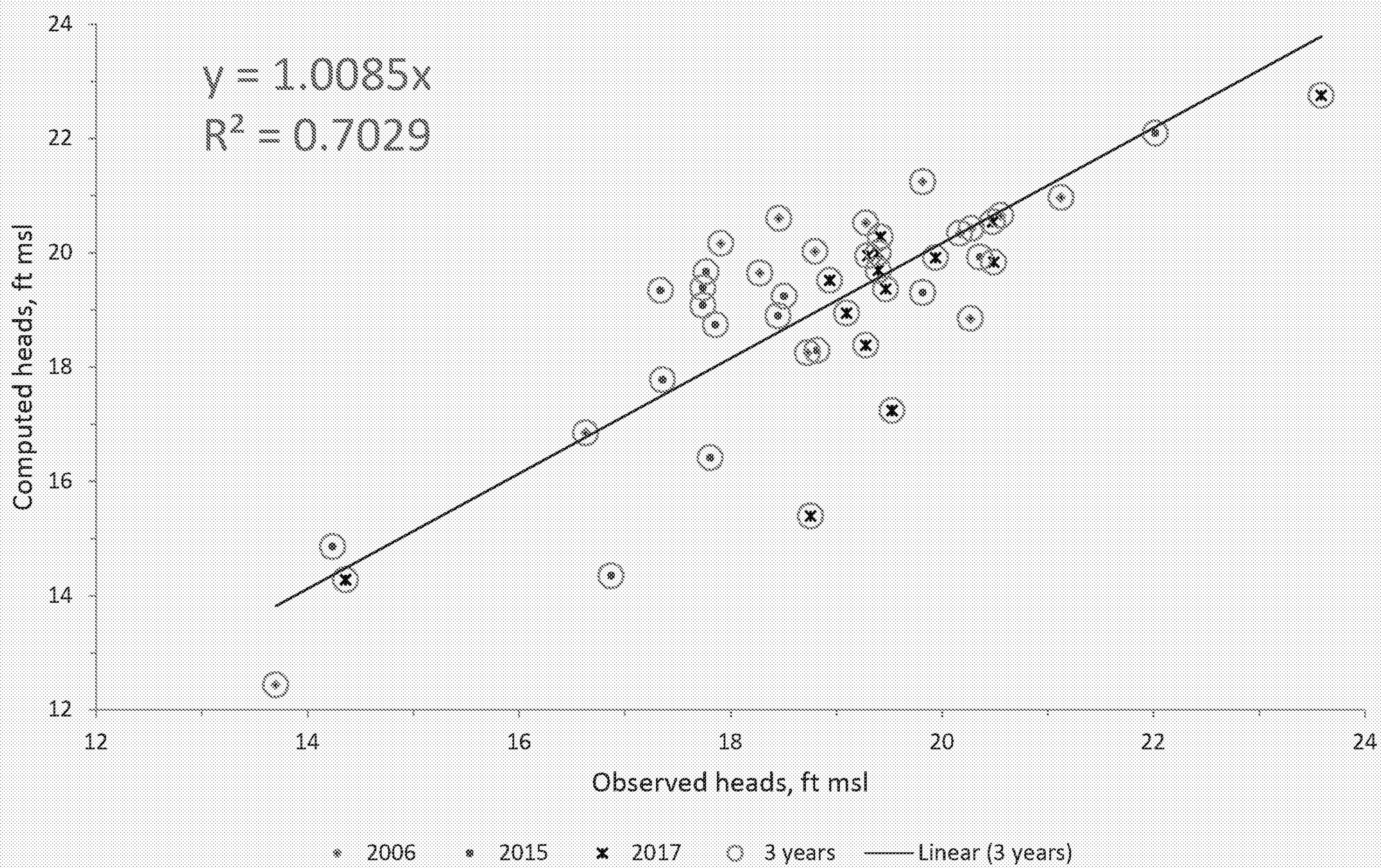
Key observation – no simulated water level mounding under saprolite

FINAL INTERIM CALIBRATION – ENTIRE MODEL DOMAIN



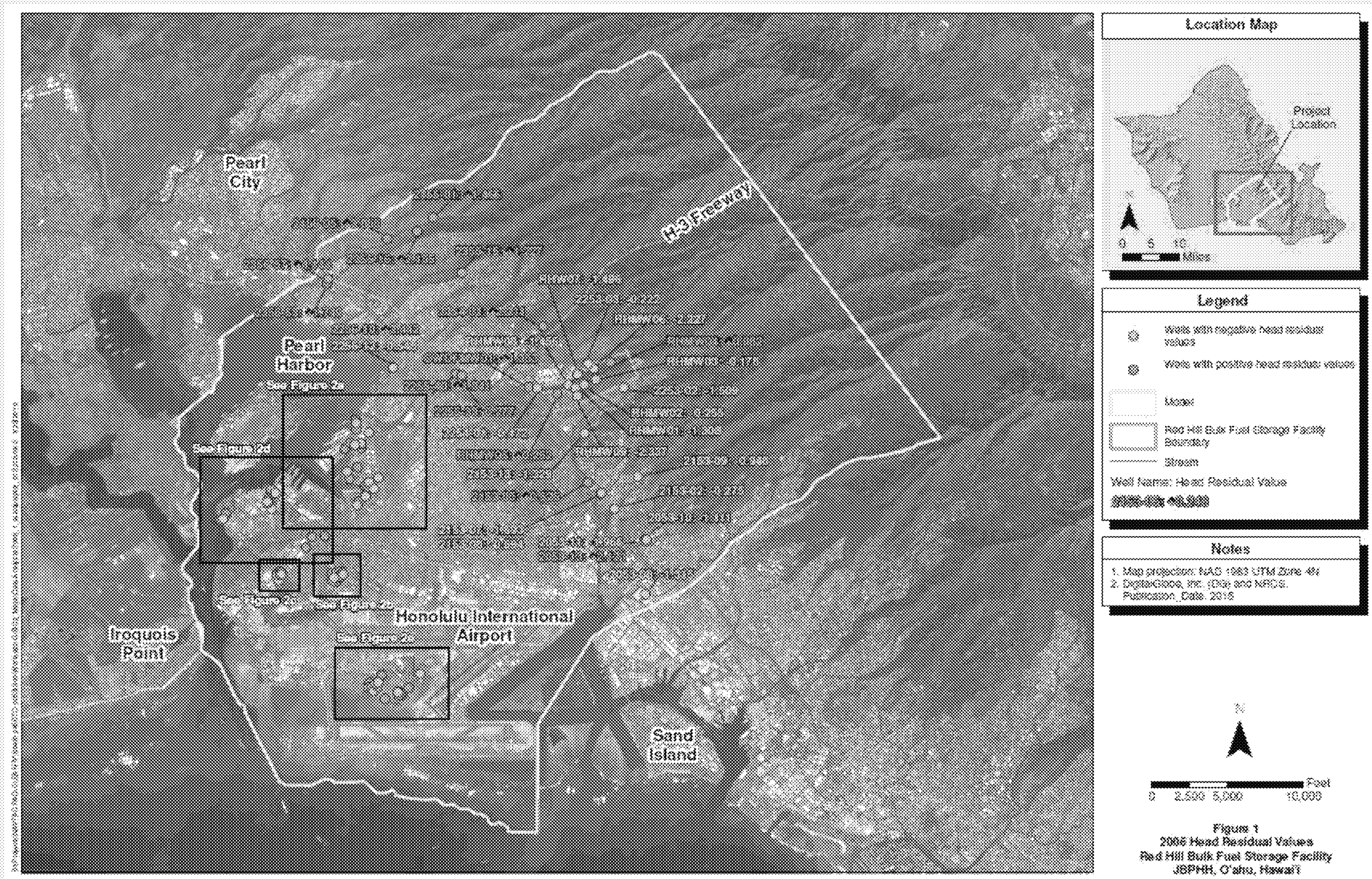
Entire model	ME = 0.59	RMS = 2.0

FINAL INTERIM CALIBRATION – RED HILL FOCUS AREA

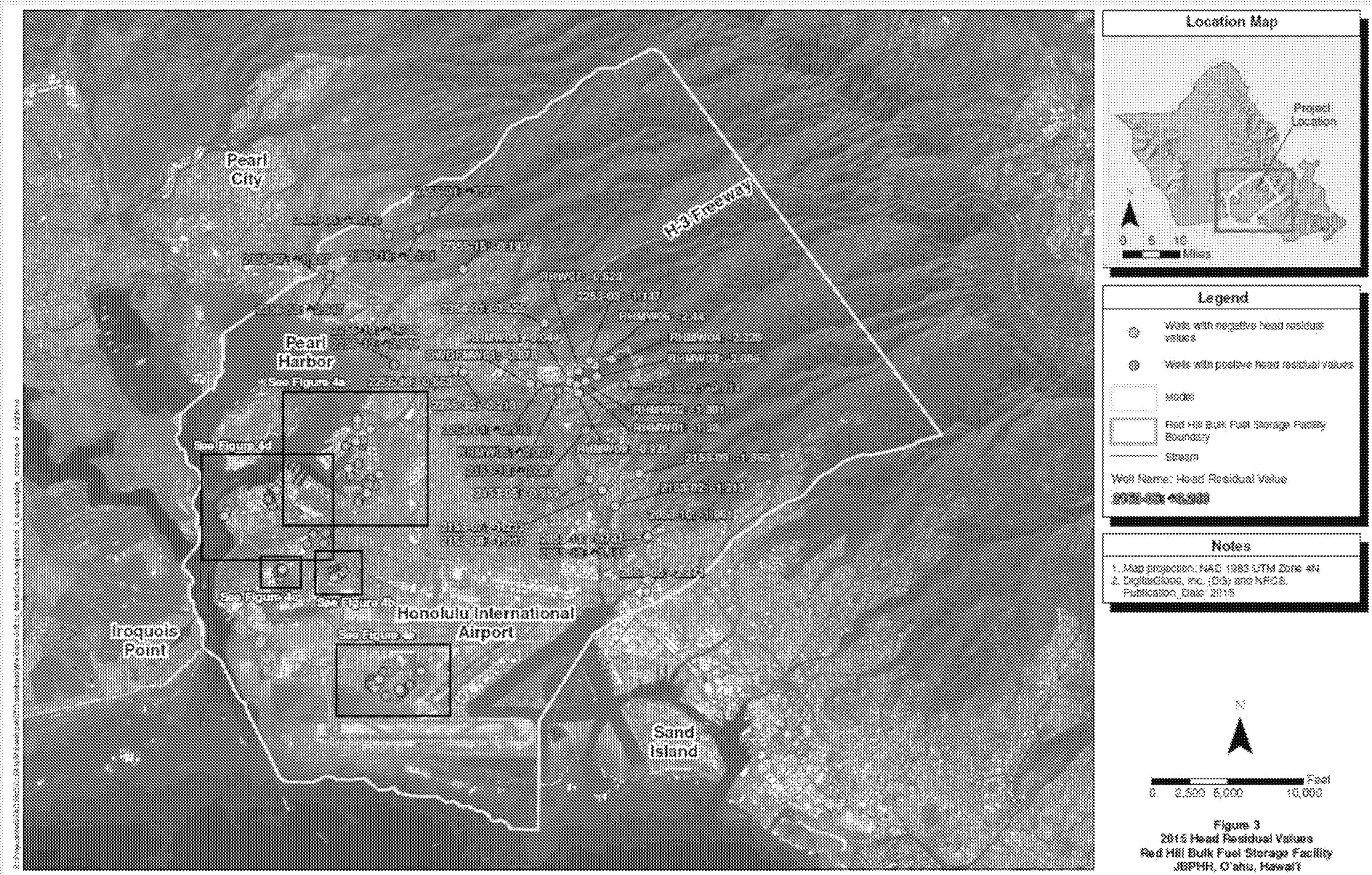


Focus Area	ME = -0.25	RMS = 1.2

DISTRIBUTIONS OF RESIDUALS 2006



DISTRIBUTIONS OF RESIDUALS 2015



DISTRIBUTIONS OF RESIDUALS 2017

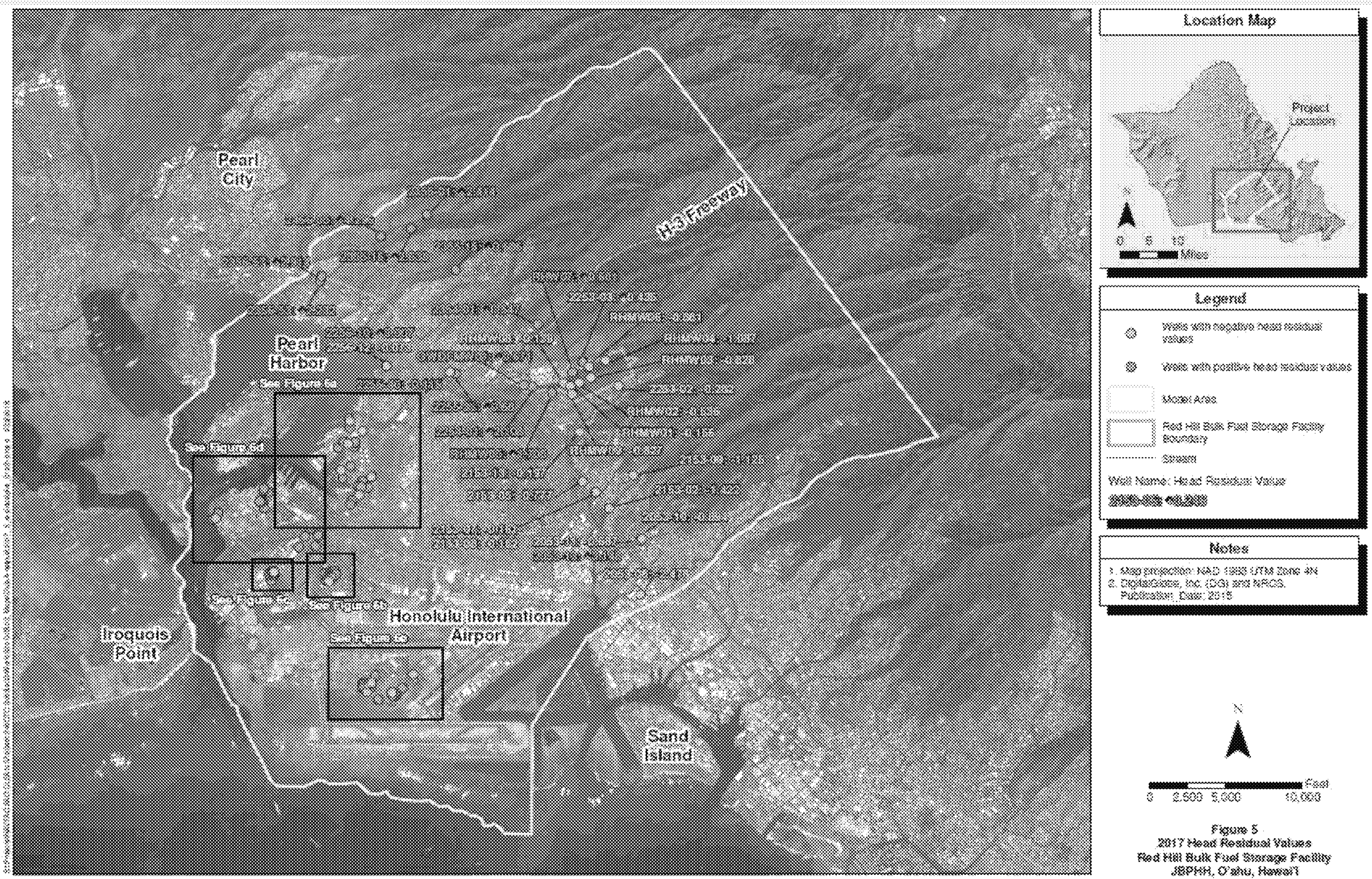
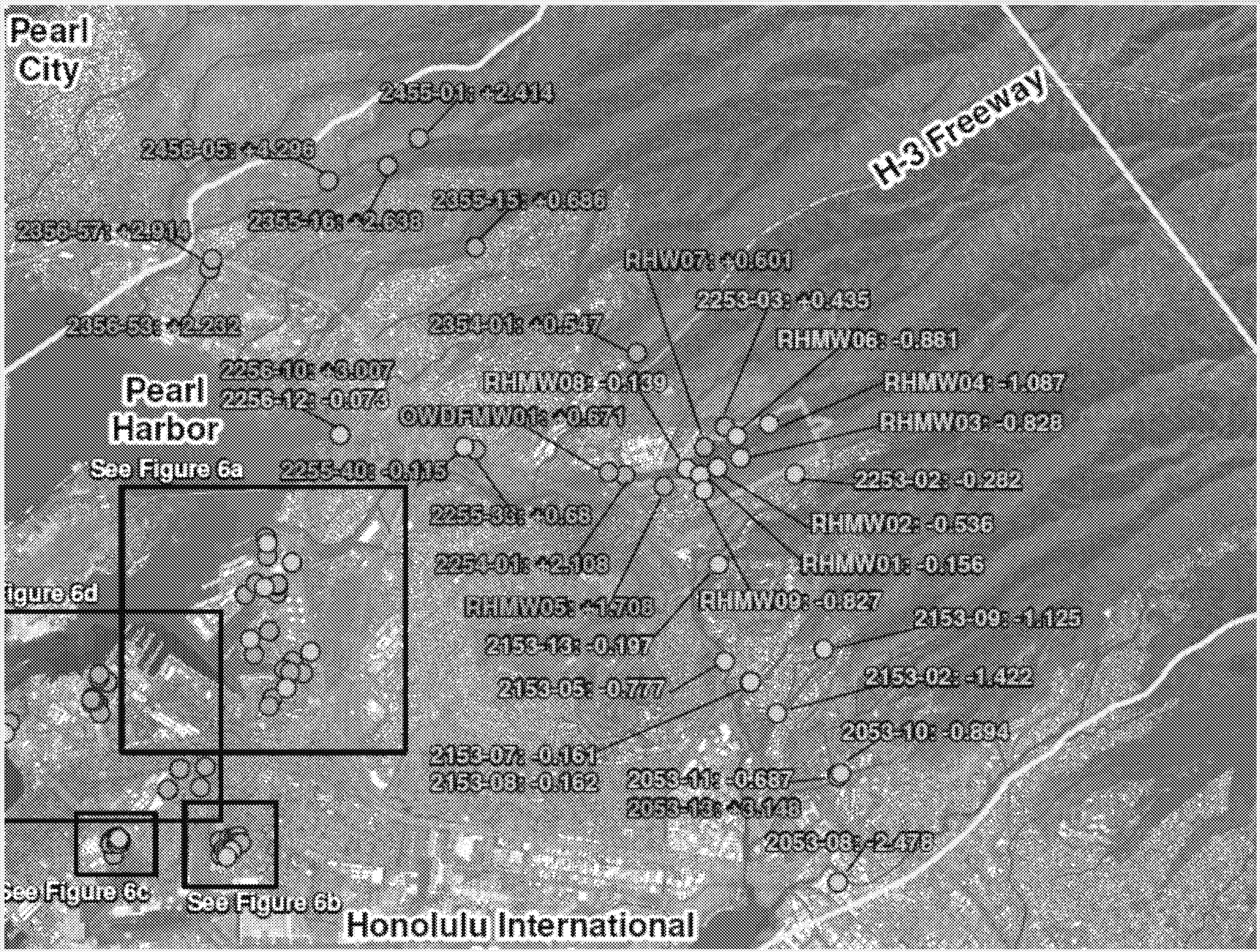


Figure 5
2017 Head Residual Values
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

DISTRIBUTIONS OF RESIDUALS 2017 ZOOMED IN



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SIMULATED GROUNDWATER VOLUMETRIC BUDGET (MGD)

Year	2006	2015	2017
Recharge	48.04	35.81	36.77
NE Inflow	22.4	22.4	22.4
NW Inflow	0	0	0
SE Inflow	0	0	0
Well discharge	37.31	28.76	27.10
Pearl Harbor at Kalauao Spring Discharge	10.9	10.0	11.6
Kalauao Spring Discharge	0.122	0.11	0.12
Seafloor discharge	22.22	20.02	20.72

Observations:

- Spring flow (correlated with WLEs at Navy ‘Aiea well) is lowest in 2015
- Recharge and pumping are lowest in 2017

CONCEPTUAL GROUNDWATER BUDGET ESTIMATES – 2006, 2015, AND 2017

Year	2006	2015	2017
Recharge	43.11	42.40	30.30
NE Inflow	22.4	22.4	22.4
NW Inflow	0	0	0
SE Inflow	0	0	0
Well discharge	43.12	37.93	31.46
Pearl Harbor Spring at Kalauao discharge	12.12	9.56	11.81
Kalauao Spring discharge	0.328	0.224	0.315
Seafloor discharge	9.94	17.09	9.12

Observations:

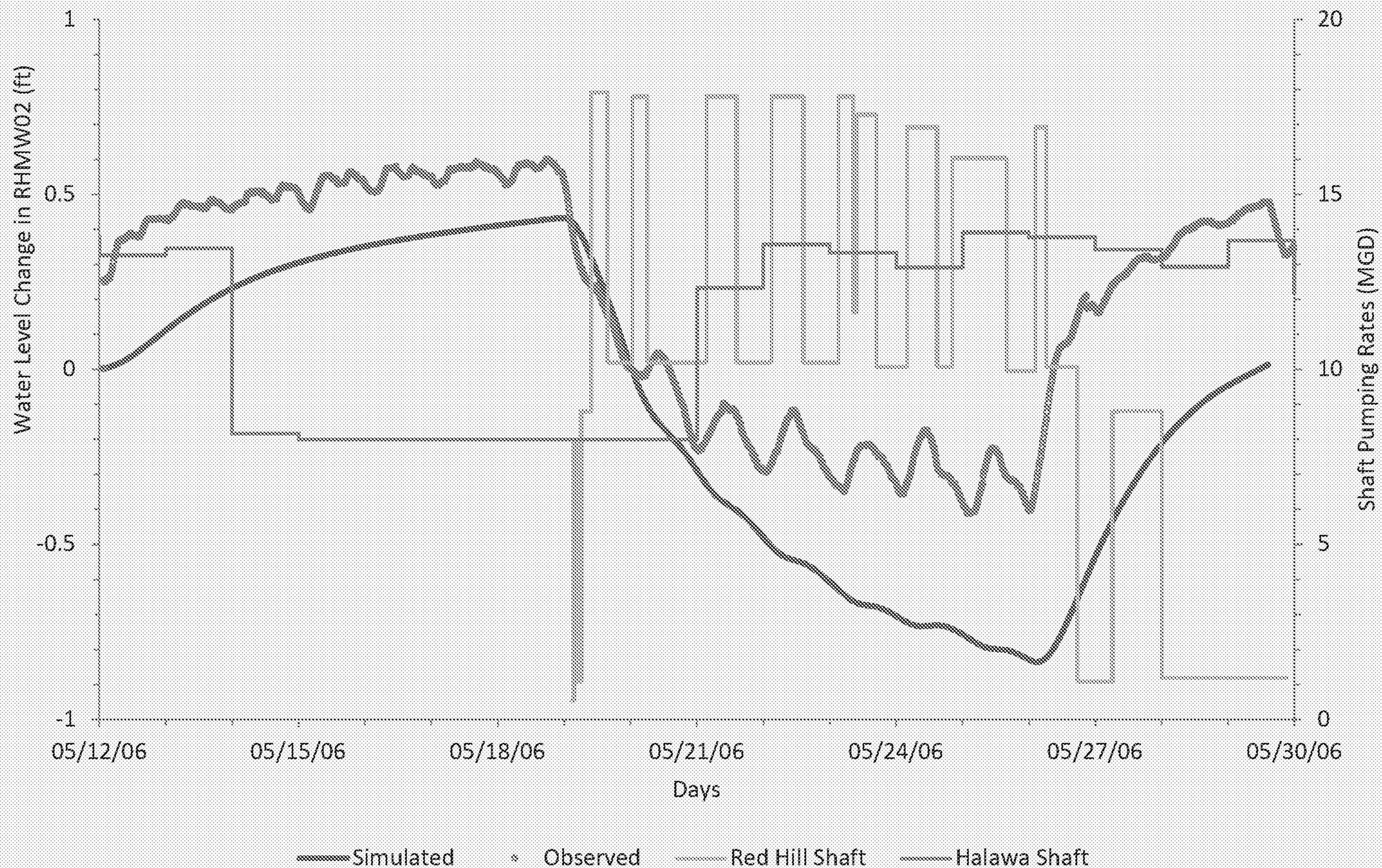
- Spring flow (correlated with WLEs at Navy 'Aiea well) is lowest in 2015
- Recharge and pumping are lowest in 2017

INTERIM MODEL - TRANSIENT SYNOPTIC STUDY STORAGE PARAMETERS

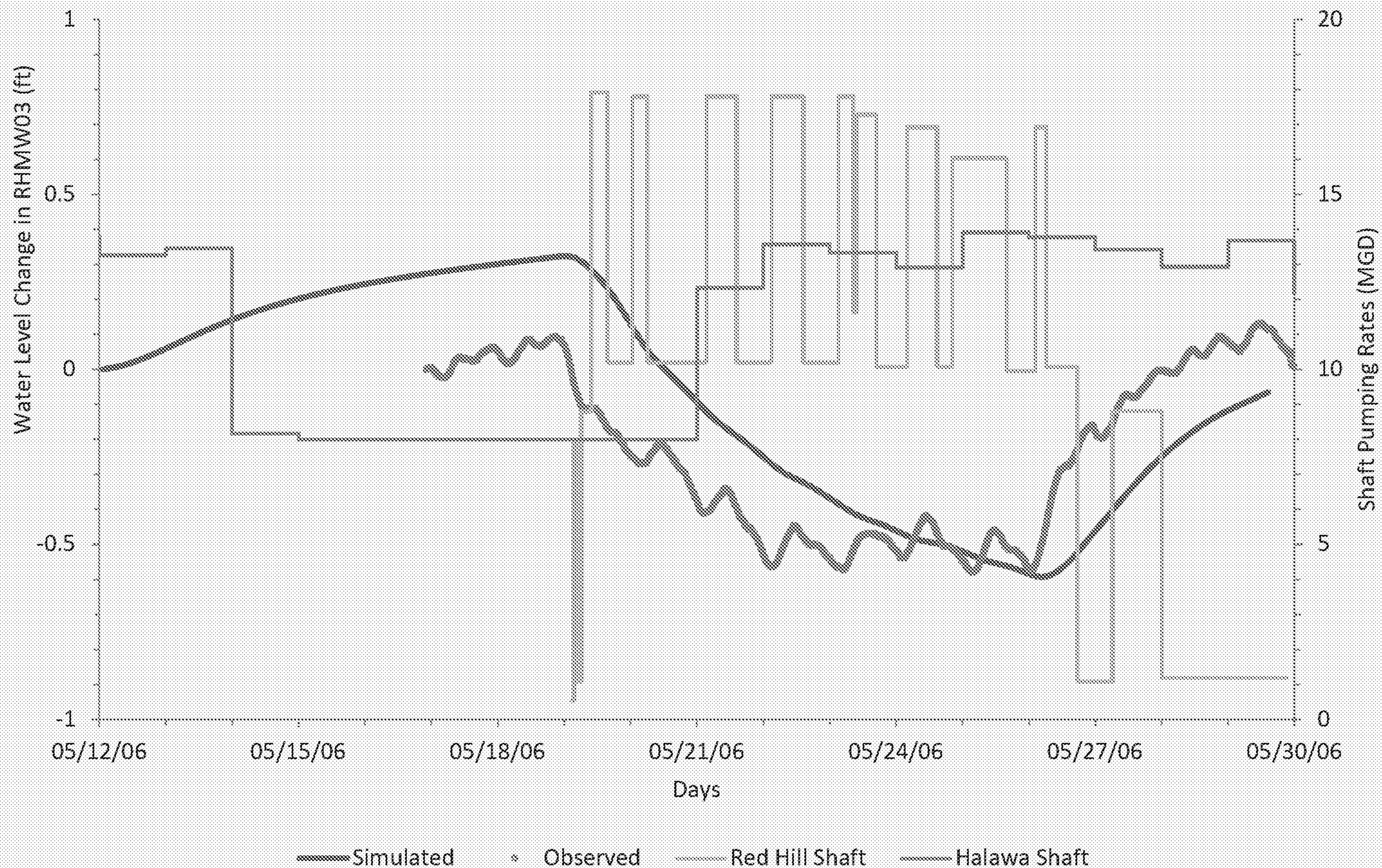
	Caprock	Valley Fill	Saprolite	Basalt
Specific yield [-]	0.1	0.15	0.15	0.031
Specific storage [ft^{-1}]	3.05×10^{-5}	1.52×10^{-5}	1.52×10^{-5}	1.07×10^{-5}

Notes:
1. Specific yield and specific storage of caprock and basalt are referenced from Table 11 (TEC, 2007)
2. Specific storage of saprolite is assumed to be the same as valley fill from Table 11 (TEC, 2007)

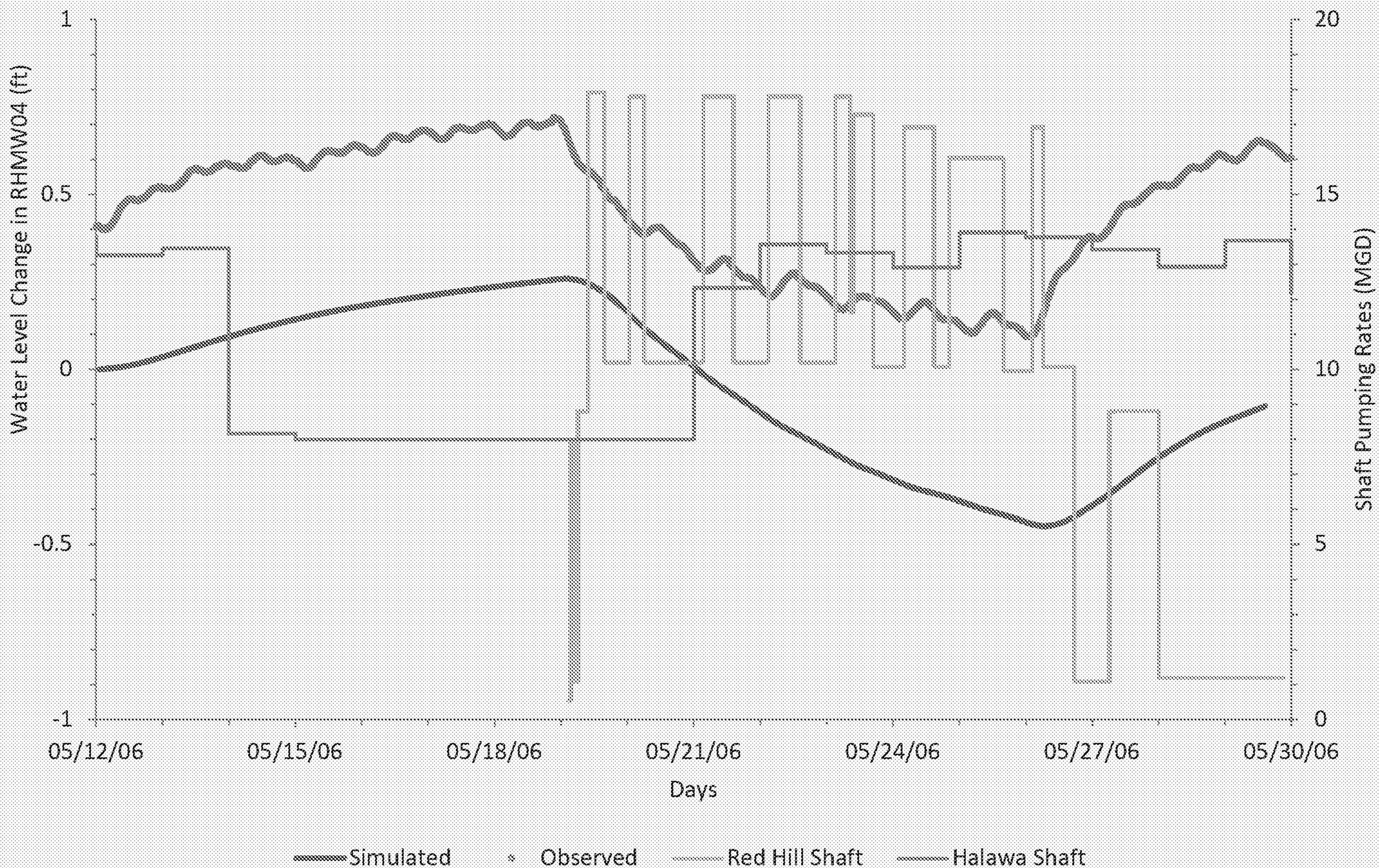
2006 TRANSIENT SYNOPTIC STUDY RHMW02



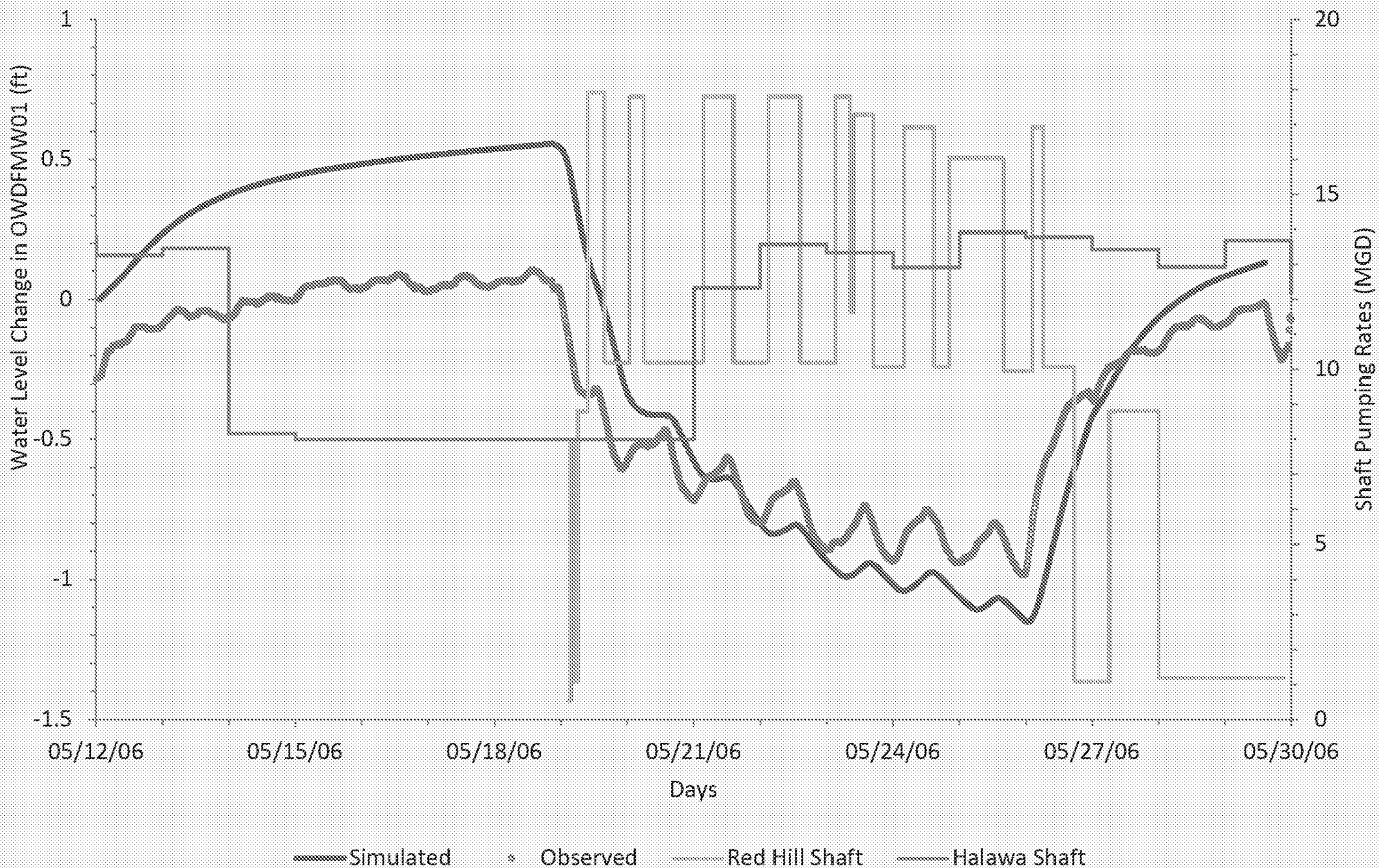
2006 TRANSIENT SYNOPTIC STUDY RHMW03



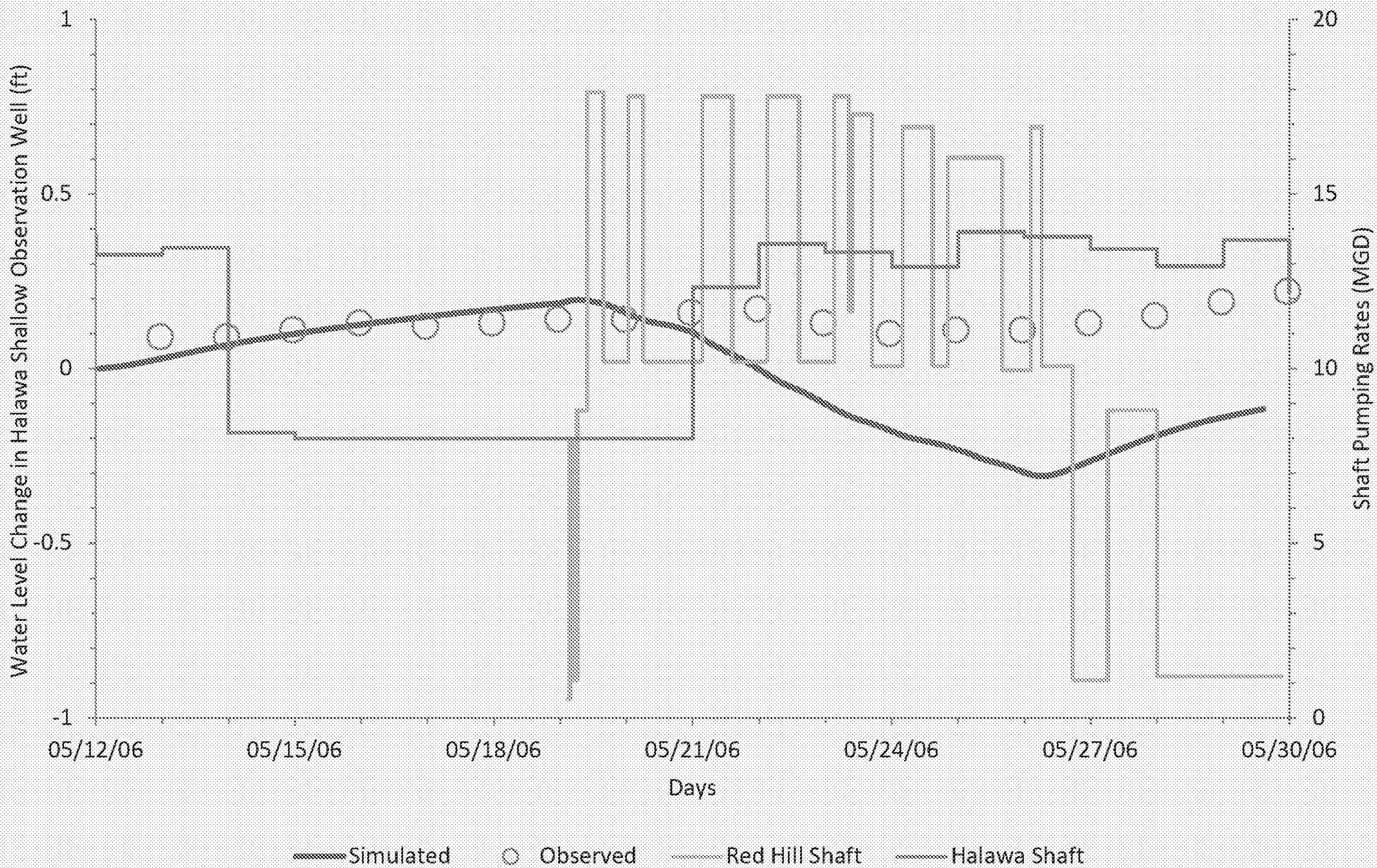
2006 TRANSIENT SYNOPTIC STUDY RHMW04



2006 TRANSIENT SYNOPTIC STUDY OWDF MW01

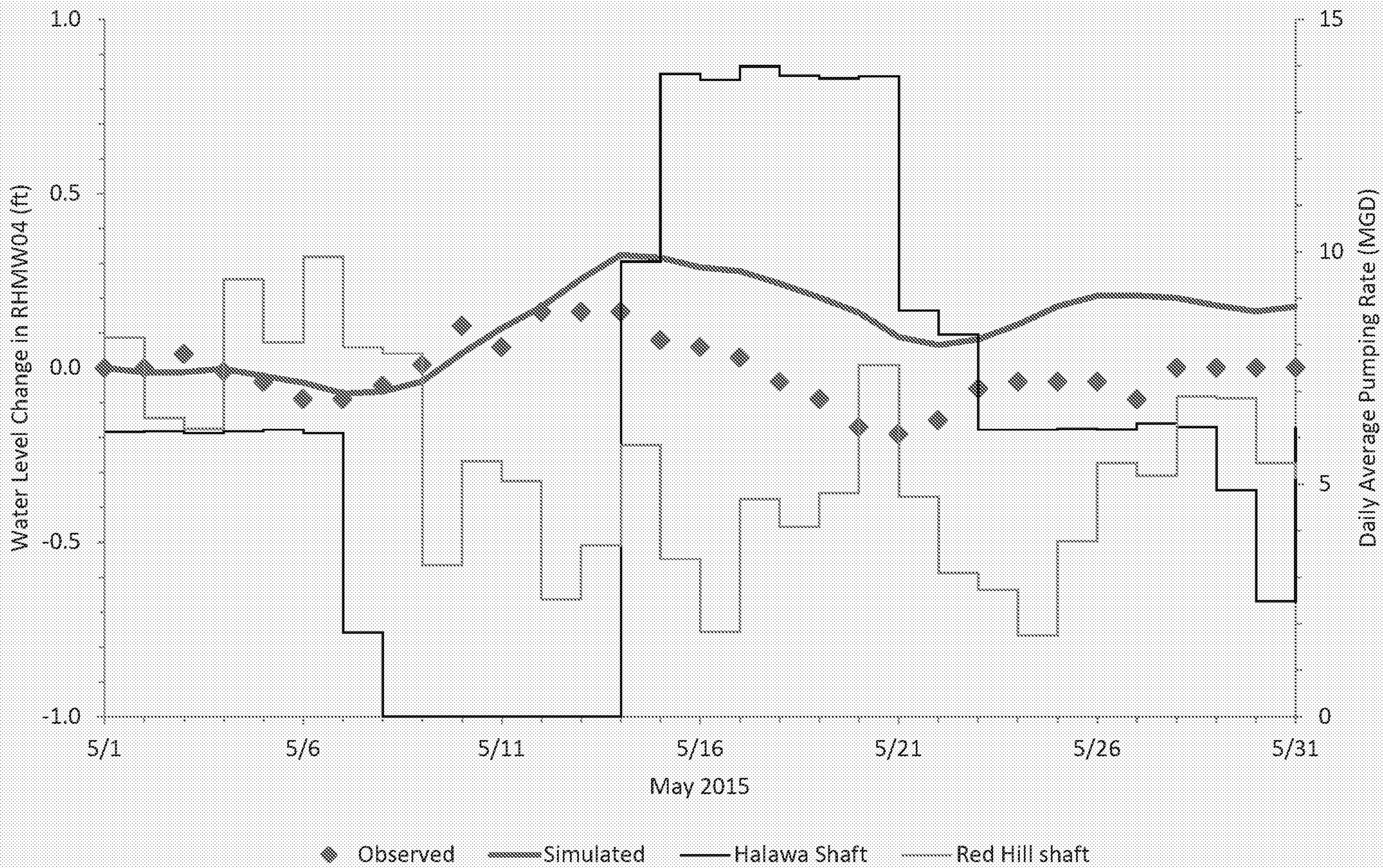


2006 TRANSIENT SYNOPTIC STUDY HALAWA SHALLOW OBS (2255-33)



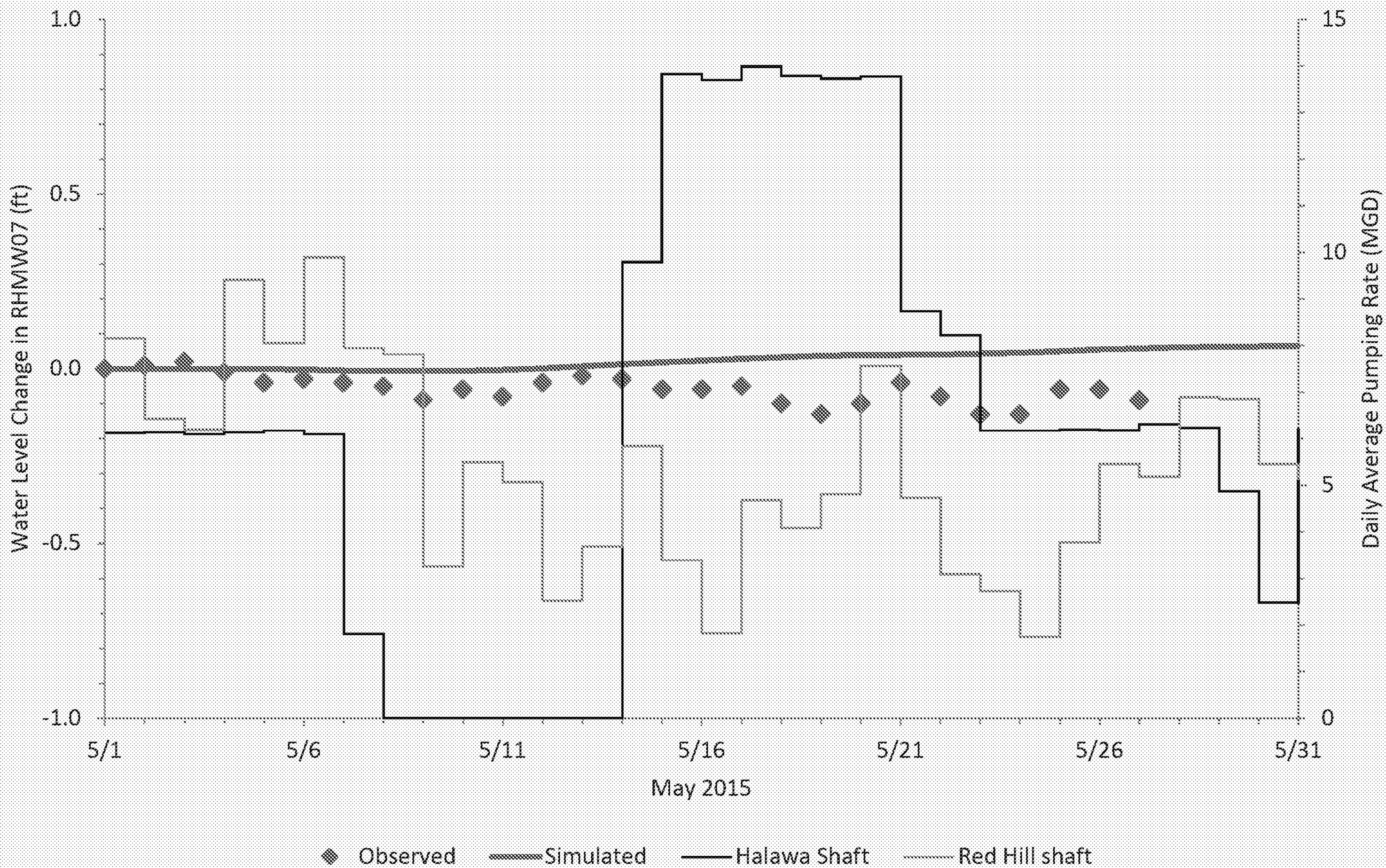
2015 TRANSIENT SYNOPTIC STUDY RHMW04

Simulation initiated with steady-state conditions of Halawa Shaft pumping 5.91 MGD and Red Hill Shaft pumping 7 MGD



2015 TRANSIENT SYNOPTIC STUDY
RHMW07

Simulation initiated with steady-state conditions of Halawa Shaft pumping 5.91 MGD and Red Hill Shaft pumping 7 MGD



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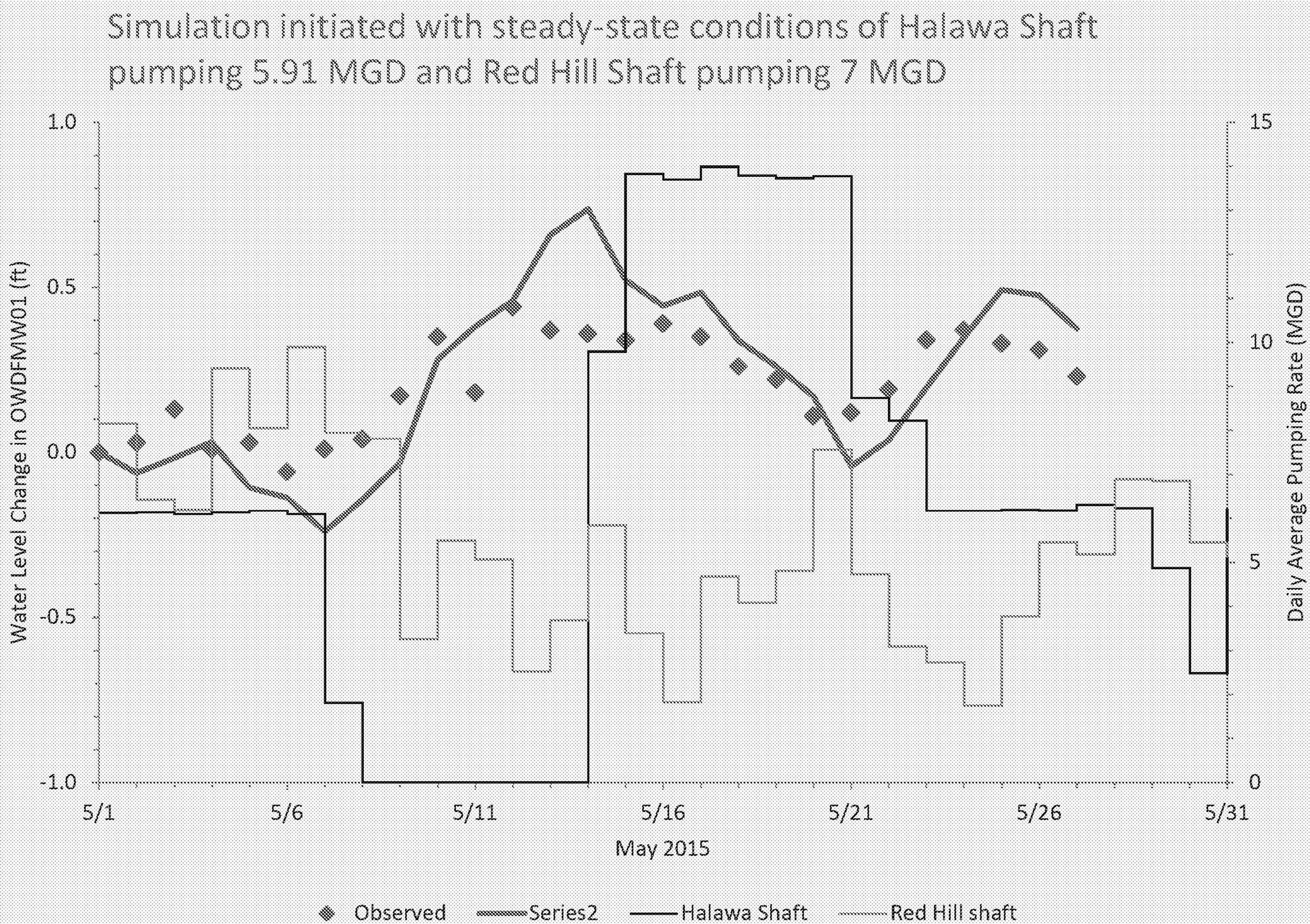
2015 TRANSIENT SYNOPTIC STUDY OWDFMW01



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2015 TRANSIENT SYNOPTIC STUDY HALAWA T45 (2255-33)

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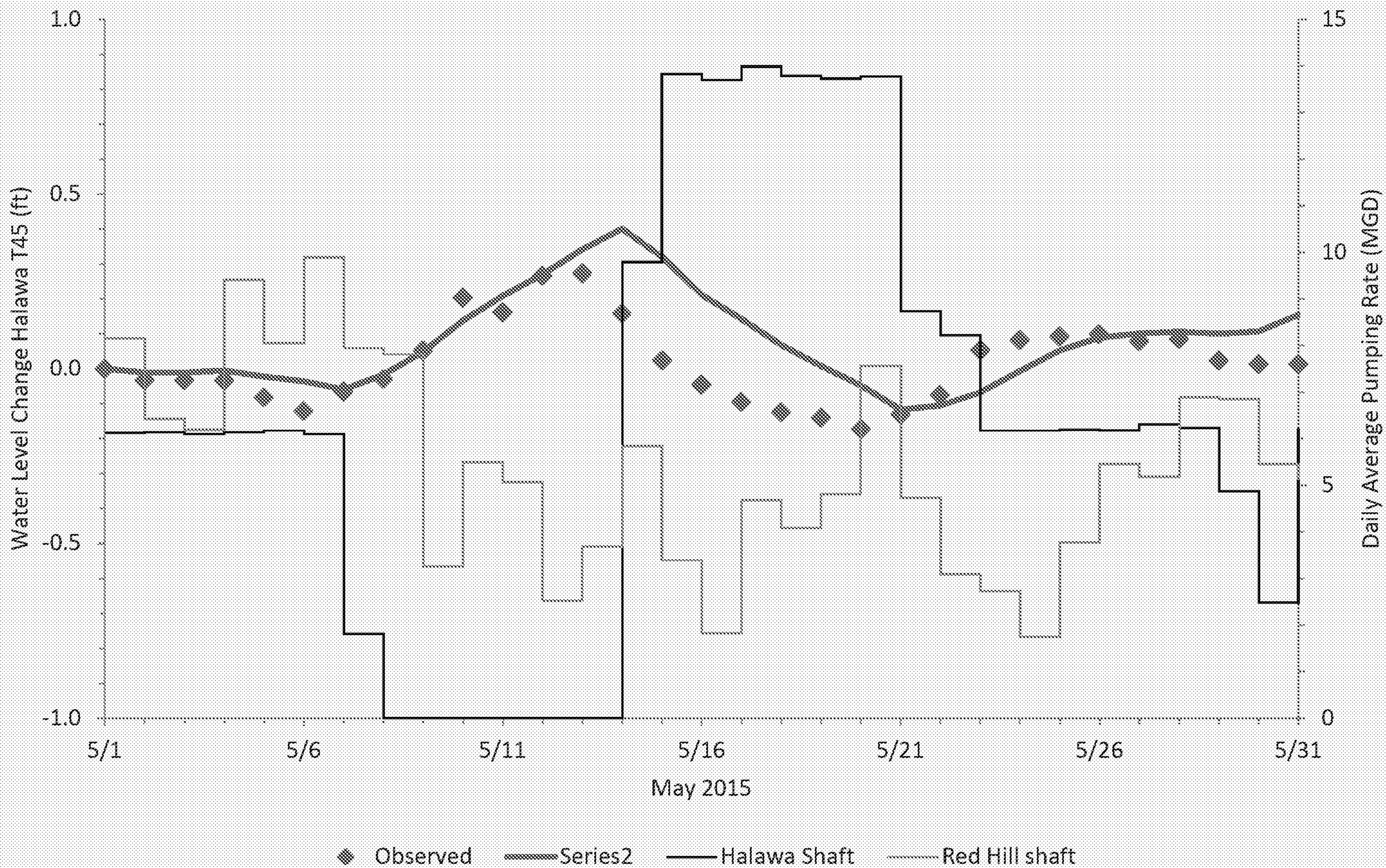
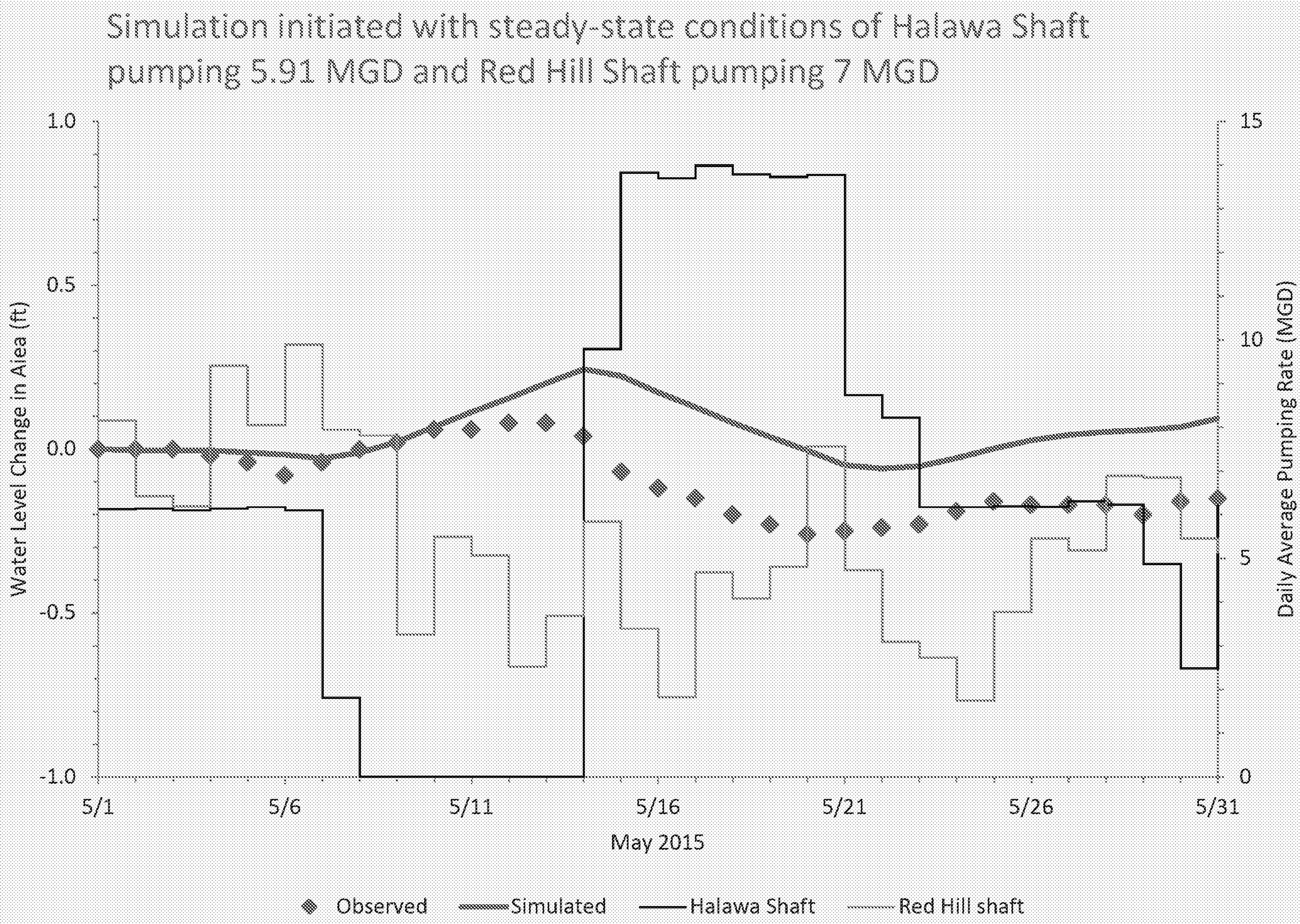
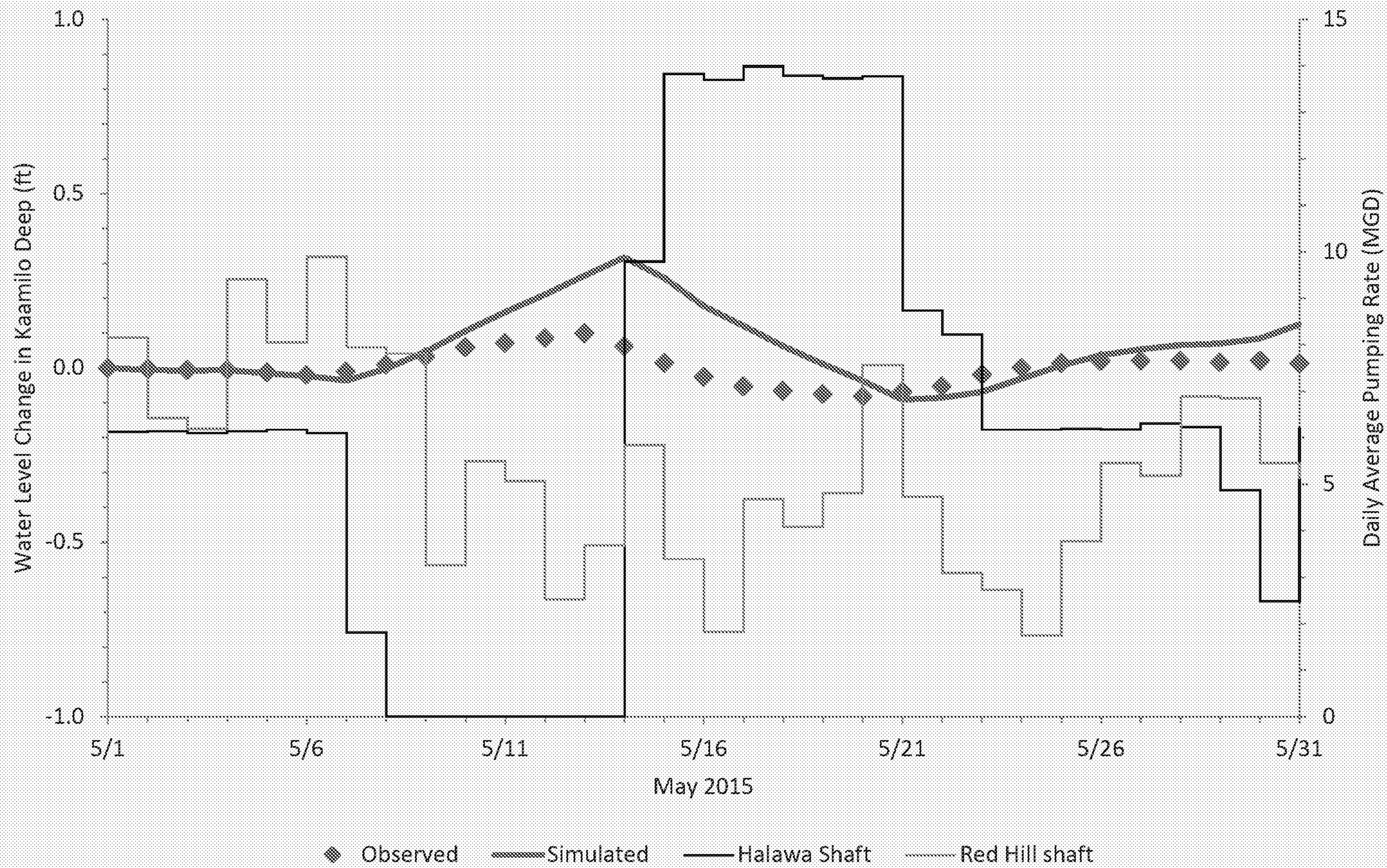


2015 TRANSIENT SYNOPTIC STUDY NAVY AIEA (2256-10)



2015 TRANSIENT SYNOPTIC STUDY KA'AMILO DEEP (2355-15)

Simulation initiated with steady-state conditions of Halawa Shaft pumping 5.91 MGD and Red Hill Shaft pumping 7 MGD



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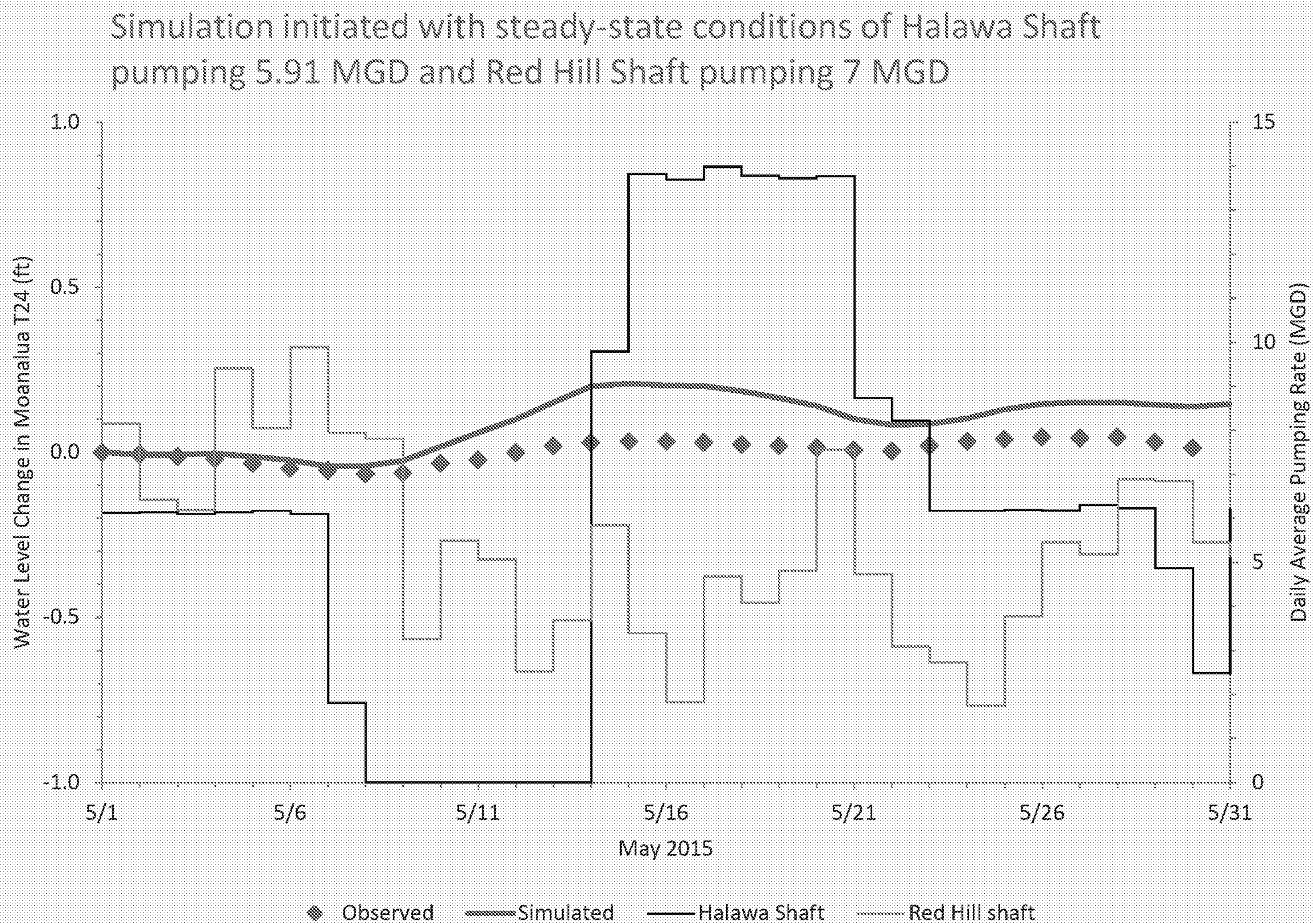
2015 TRANSIENT SYNOPTIC STUDY MOANALUA T24 (2153-09)



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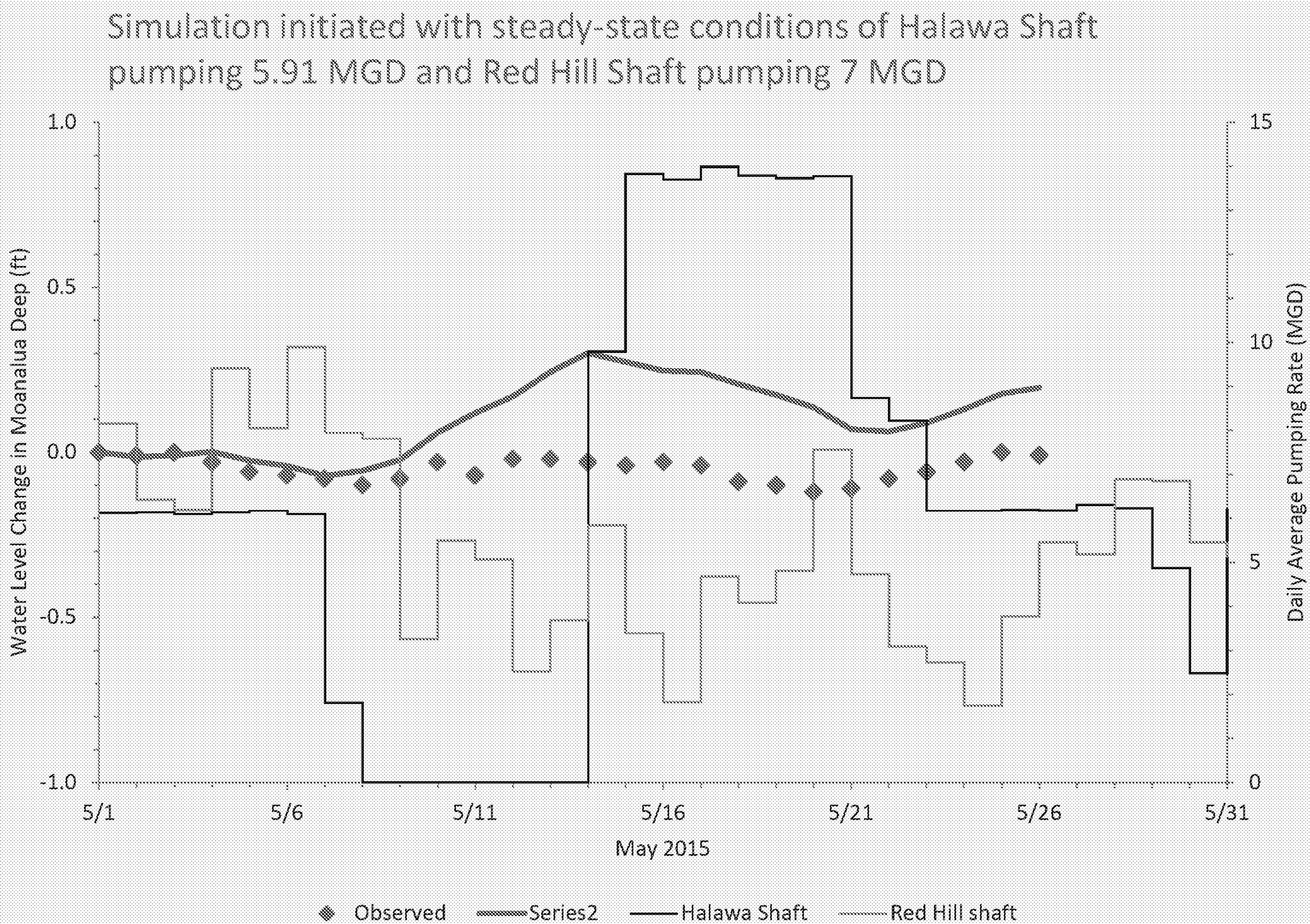
2015 TRANSIENT SYNOPTIC STUDY MOANALUA DEEP (2153-05)



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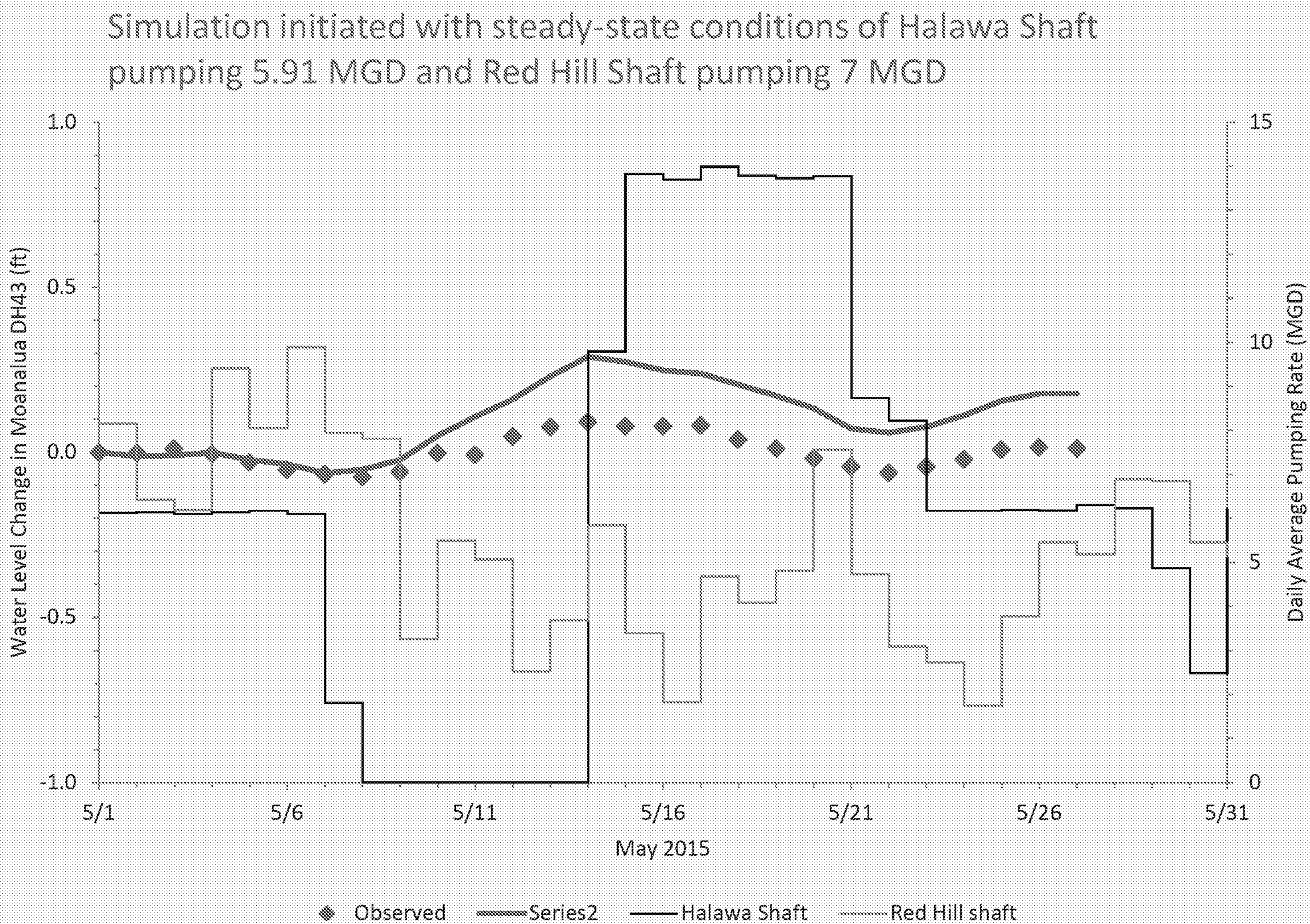
2015 TRANSIENT SYNOPTIC STUDY MOANALUA DH43 (2253-02)



KEY HEAD DIFFERENCES

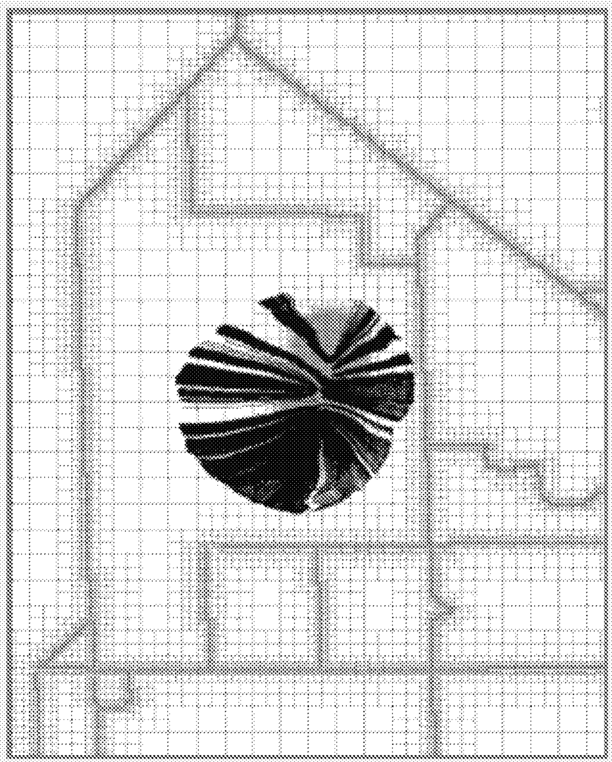
Wells	Measured difference with Halawa Shaft			Simulated difference with Halawa Shaft			Simulated minus measured difference		
	2006	2015	2017	2006	2015	2017	2006	2015	2017
OWDFMW01	6.57	3.12	4.92	6.42	2.93	4.10	-0.15	-0.19	-0.82
RHMW01	5.10	3.62	5.11	7.59	3.89	5.10	2.49	0.27	-0.01
RHMW02	6.47	3.50	5.04	7.92	4.23	5.43	1.45	0.73	0.39
RHMW03	6.86	3.50	5.04	8.23	4.54	5.73	1.37	1.04	0.69
RHMW04	7.43	3.53	5.06	8.54	4.83	6.02	1.11	1.30	0.95
RHMW05	5.03	3.57	5.17	5.82	1.57	2.97	0.79	-2.00	-2.20
RHMW06	**4.76**	**3.10**	**4.94**	**8.18**	**4.49**	**5.68**	**3.42**	**1.39**	**0.74**
RHMW07	9.16	7.78	9.23	11.84	7.24	8.48	2.68	-0.54	-0.75
RHMW08	4.58	4.58	4.74	7.21	3.45	4.68	2.63	-1.14	-0.07
RHMW09	4.21	4.21	4.58	7.74	4.05	5.25	3.53	-0.16	0.67

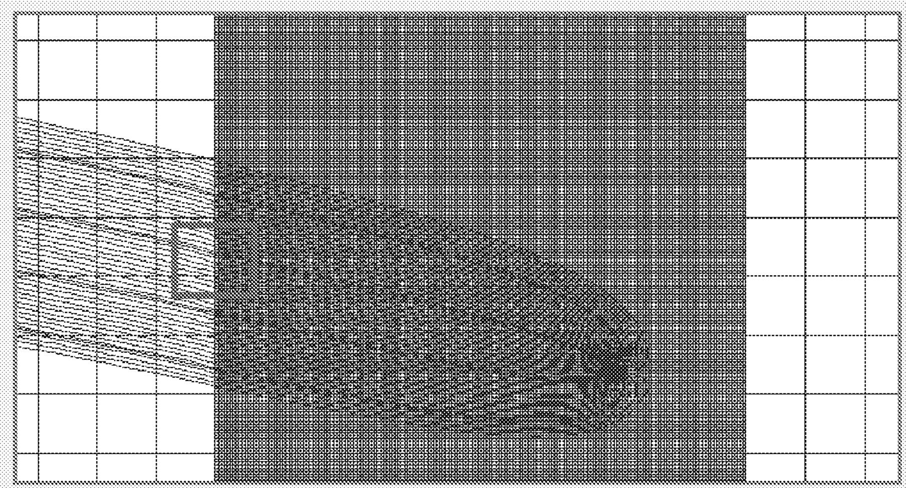
As a measure of conservatism, the simulated slope in water level from focus area wells towards Halawa Shaft is generally larger (positive) compared to actual water level measurements

PARTICLE TRACKING SIMULATIONS

PARTICLE TRACKING – MODPATH VERSION

- mod-PATH3DU
- Available for cost-free download from SSPA website
- Results compare well with USGS version for unstructured grids – MODPATH7

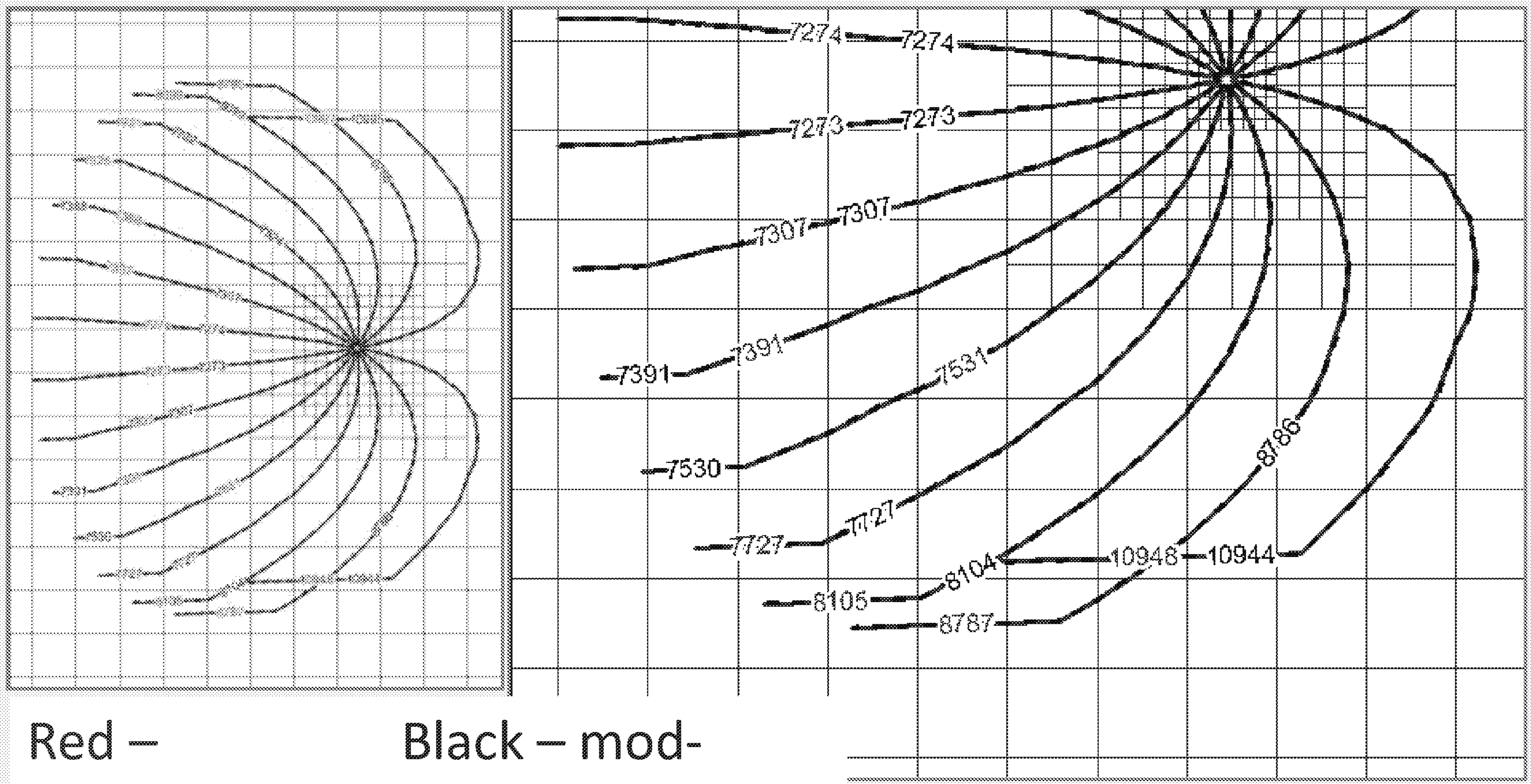




Courtesy of Chris Muffels, SSPA

COMPARISON WITH MODPATH7

Example 2A from MODPATH7 Manual



Red – MODPATH7

Black – mod-PATH3DU

Courtesy of Chris Muffels, SSPA

INTERIM MODEL PARTICLE TRACKING SCENARIOS BASED ON CALIBRATED BASE-CASE MODEL

Scenario no.	Tracking Direction	Particle Release Location	Halawa Shaft	Q, mgd	Red Hill Shaft	Q, mgd	Moanalua Wells	Q, mgd
1	forward	Box 1A	on	16	on	4.659	on	3.7
2	forward	Box 1A	on	16	off	0	on	3.7
3	backward	Red Hill Shaft	on	16	on	4.659	on	3.7
4	backward	Halawa shaft	on	16	on	4.659	on	3.7
5	backward	Halawa shaft	on	16	off	0	on	3.7
6	backward	Moanalua wells	on	16	on	4.659	on	3.7
7	backward	Moanalua wells	on	16	off	0	on	3.7

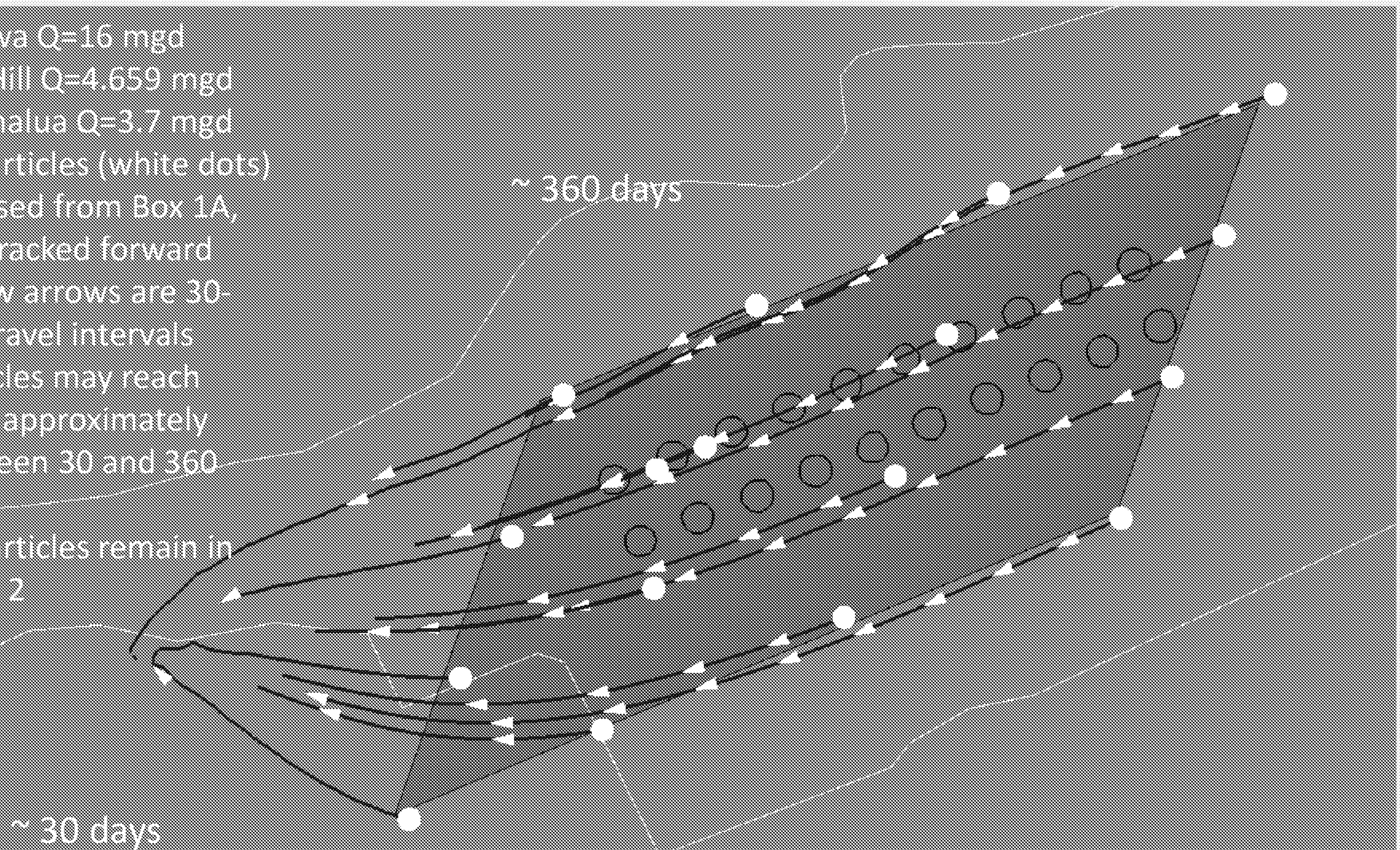
Notes:

1. Particle tracking simulations are based on updated interim model calibration

2. All other wells are pumping at 2017 average rates
3. Particle tracking code: mod-PATH3DU (S. S. Papadopulos & Associates, Inc., 2016)

SCENARIO 1 (FORWARD TRACKING FROM BOX 1A)

- Halawa Q=16 mgd
- Red Hill Q=4.659 mgd
- Moanalua Q=3.7 mgd
- 16 particles (white dots) released from Box 1A, and tracked forward
- Yellow arrows are 30-day travel intervals
- Particles may reach shaft approximately between 30 and 360 days
- All particles remain in Layer 2



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INTERIM MODEL PARTICLE TRACKING SCENARIOS

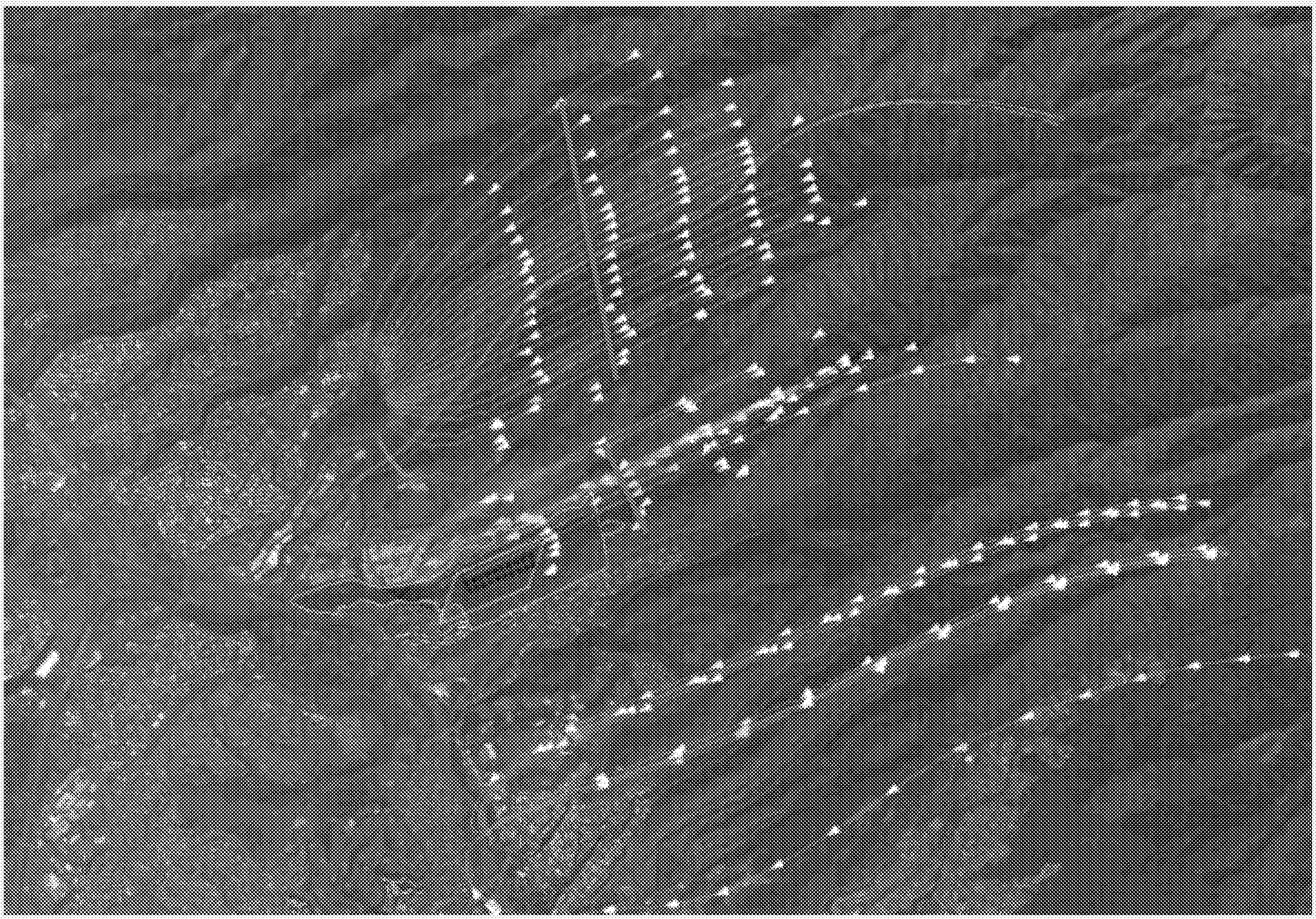
Scenario no.	Tracking Direction	Particle Release Location	Halawa Shaft	Q, mgd	Red Hill Shaft	Q, mgd	Moanalua Wells	Q, mgd
1	forward	Box 1A	on	16	on	4.659	on	3.7
2	forward	Box 1A	on	16	off	0	on	3.7
3	backward	Red Hill shaft	on	16	on	4.659	on	3.7
4	backward	Halawa shaft	on	16	on	4.659	on	3.7
5	backward	Halawa shaft	on	16	off	0	on	3.7
6	backward	Moanalua wells	on	16	on	4.659	on	3.7
7	backward	Moanalua wells	on	16	off	0	on	3.7

Notes:

1. Particle tracking simulations are based on updated interim model calibration

2. All other wells are pumping at 2017 average rates
3. Particle tracking code: mod-PATH3DU (S. S. Papadopulos & Associates, Inc., 2016)

SCENARIOS 3, 4, AND 6 (RED HILL SHAFT ON)



- Arrows are 1-year time intervals
- Pathline colors
  - Layer 1
  - Layer 2
  - Layer 3
  - Layer 4
  - Layer 5

Colored pathlines are based on beta version of GMS, which has not been officially released yet.

INTERIM MODEL PARTICLE TRACKING SCENARIOS

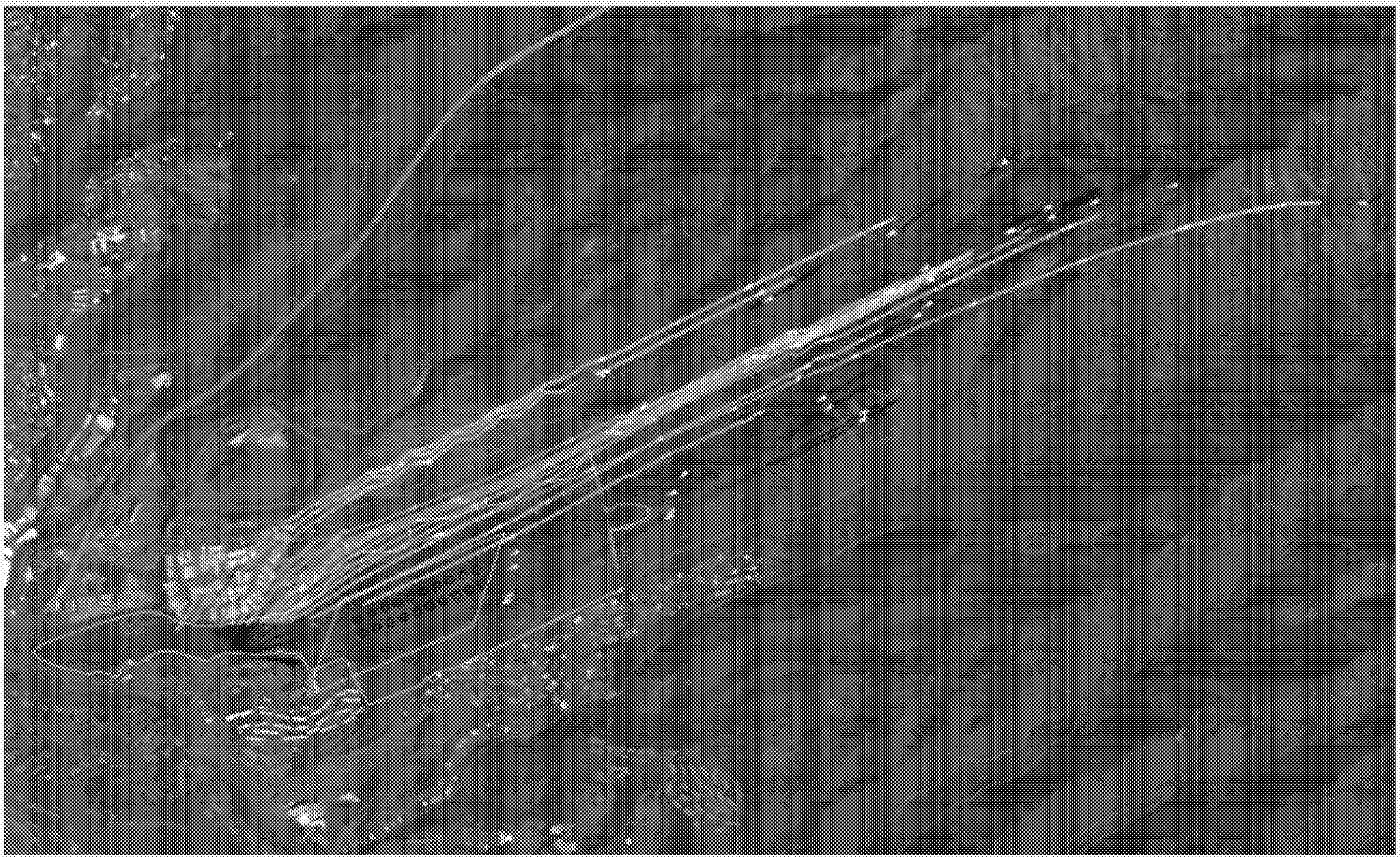
Scenario no.	Tracking Direction	Particle Release Location	Halawa Shaft	Q, mgd	Red Hill Shaft	Q, mgd	Moanalua Wells	Q, mgd
1	forward	Box 1A	on	16	on	4.659	on	3.7
2	forward	Box 1A	on	16	off	0	on	3.7
3	backward	Red Hill shaft	on	16	on	4.659	on	3.7
4	backward	Halawa shaft	on	16	on	4.659	on	3.7
5	backward	Halawa shaft	on	16	off	0	on	3.7
6	backward	Moanalua wells	on	16	on	4.659	on	3.7
7	backward	Moanalua wells	on	16	off	0	on	3.7

Notes:

1. Particle tracking simulations are based on updated interim model calibration

2. All other wells are pumping at 2017 average rates
3. Particle tracking code: mod-PATH3DU (S. S. Papadopulos & Associates, Inc., 2016)

SCENARIO 3 - ZOOMED IN TO RED HILL AREA (RED HILL SHAFT ON)



Inverse particle tracks
Particles released at __ immediately upgradient of Red Hill shaft cells
Arrows are 1-year time intervals
Pathline colors
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

INTERIM MODEL PARTICLE TRACKING SCENARIOS

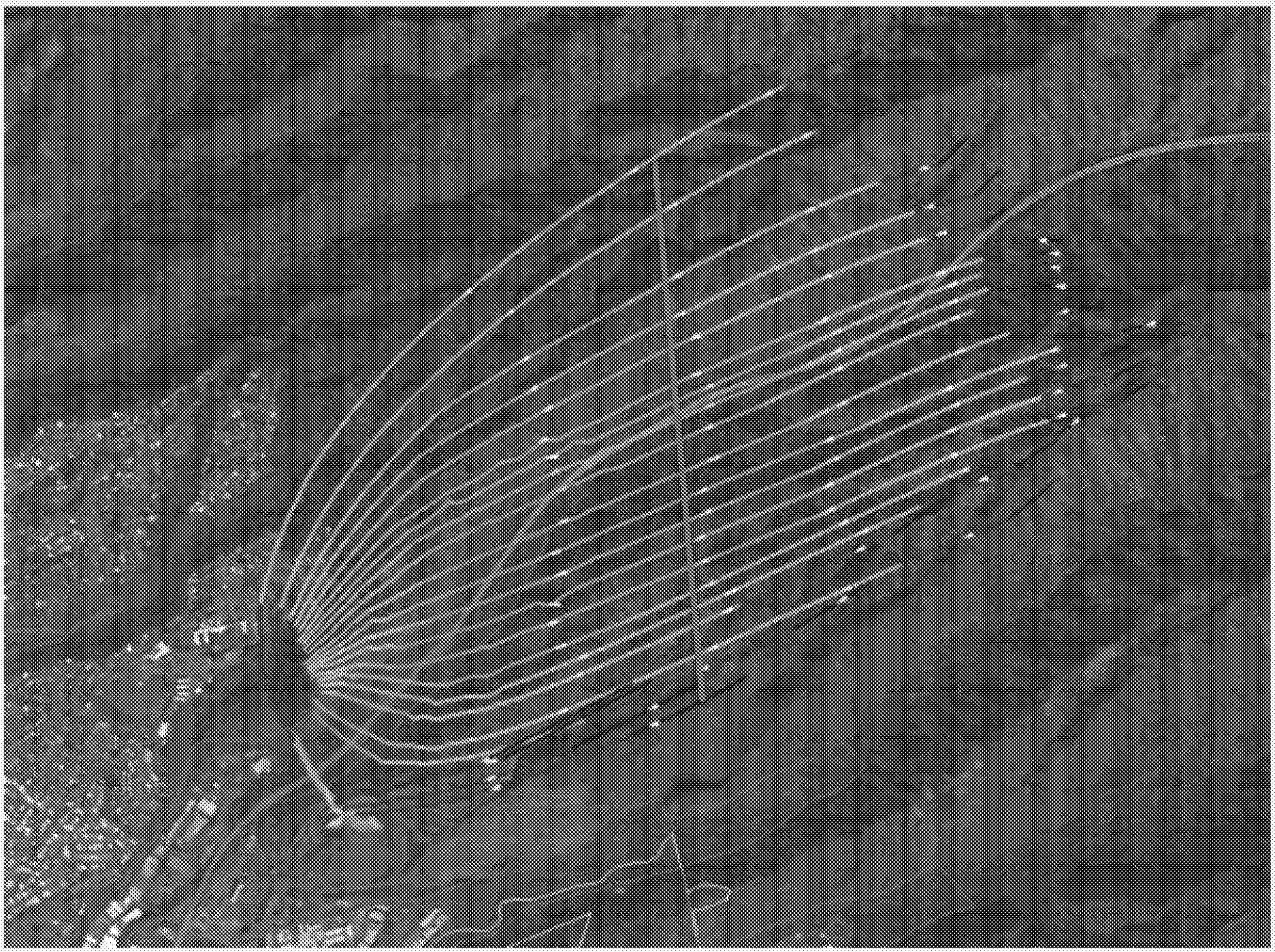
Scenario no.	Tracking Direction	Particle Release Location	Halawa Shaft	Q, mgd	Red Hill Shaft	Q, mgd	Moanalua Wells	Q, mgd
1	forward	Box 1A	on	16	on	4.659	on	3.7
2	forward	Box 1A	on	16	off	0	on	3.7
3	backward	Red Hill shaft	on	16	on	4.659	on	3.7
4	backward	Halawa shaft	on	16	on	4.659	on	3.7
5	backward	Halawa shaft	on	16	off	0	on	3.7
6	backward	Moanalua wells	on	16	on	4.659	on	3.7
7	backward	Moanalua wells	on	16	off	0	on	3.7

Notes:

1. Particle tracking simulations are based on updated interim model calibration

2. All other wells are pumping at 2017 average rates
3. Particle tracking code: mod-PATH3DU (S. S. Papadopulos & Associates, Inc., 2016)

SCENARIOS 4 – ZOOMED IN TO HALAWA SHAFT (RED HILL SHAFT ON)



- Inverse particle tracks
- Arrows are 1-year time intervals
- Pathline colors
  - Layer 1
  - Layer 2
  - Layer 3
  - Layer 4
  - Layer 5
- Halawa Shaft orientation will be revised in final model

Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

INTERIM MODEL PARTICLE TRACKING SCENARIOS

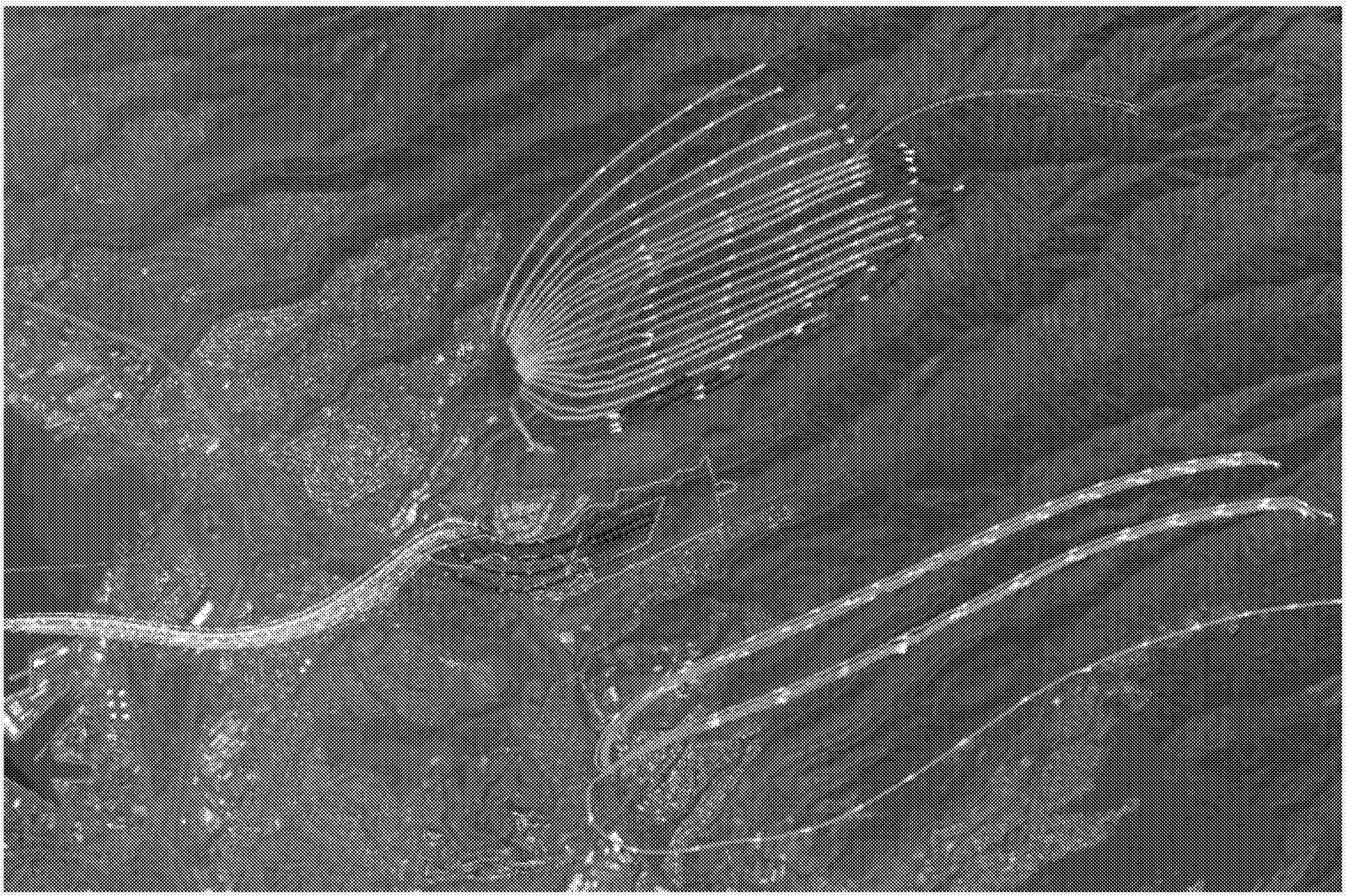
Scenario no.	Tracking Direction	Particle Release Location	Halawa Shaft	Q, mgd	Red Hill Shaft	Q, mgd	Moanalua Wells	Q, mgd
1	forward	Box 1A	on	16	on	4.659	on	3.7
2	forward	Box 1A	on	16	off	0	on	3.7
3	backward	Red Hill shaft	on	16	on	4.659	on	3.7
4	backward	Halawa shaft	on	16	on	4.659	on	3.7
5	backward	Halawa shaft	on	16	off	0	on	3.7
6	backward	Moanalua wells	on	16	on	4.659	on	3.7
7	backward	Moanalua wells	on	16	off	0	on	3.7

Notes:

1. Particle tracking simulations are based on updated interim model calibration

2. All other wells are pumping at 2017 average rates
3. Particle tracking code: mod-PATH3DU (S. S. Papadopulos & Associates, Inc., 2016)

SCENARIOS 2, 5, AND 7 (RED HILL SHAFT OFF)



- Inverse particle tracks to Moanalua wells and Halawa Shaft.
- Forward particle tracks from Red Hill facility
- Arrows are 1-year time intervals
- Pathline colors
  - Layer 1
  - Layer 2
  - Layer 3
  - Layer 4
  - Layer 5

Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

INTERIM MODEL PARTICLE TRACKING SCENARIOS

Scenario no.	Tracking Direction	Particle Release Location	Halawa Shaft	Q, mgd	Red Hill Shaft	Q, mgd	Moanalua Wells	Q, mgd
1	forward	Box 1A	on	16	on	4.659	on	3.7
2	forward	Box 1A	on	16	off	0	on	3.7
3	backward	Red Hill Shaft	on	16	on	4.659	on	3.7
4	backward	Halawa shaft	on	16	on	4.659	on	3.7
5	backward	Halawa shaft	on	16	off	0	on	3.7
6	backward	Moanalua wells	on	16	on	4.659	on	3.7
7	backward	Moanalua wells	on	16	off	0	on	3.7

Notes:

1. Particle tracking simulations are based on updated interim model calibration

2. All other wells are pumping at 2017 average rates
3. Particle tracking code: mod-PATH3DU (S. S. Papadopulos & Associates, Inc., 2016)

SCENARIO 2 - ZOOMED IN TO RED HILL AREA (RED HILL SHAFT OFF)

Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

- Arrows are 1 year time intervals
- Pathline colors
    - Layer 1
    - Layer 2
    - Layer 3
    - Layer 4
    - Layer 5

SENSITIVITY METRICS

SENSITIVITY METHODOLOGY

1. Change one parameter value to reasonable low value and simulate steady-state 2006, 2015 and 2017 conditions; evaluate calibration statistics, scatterplots, drain fluxes, and WLE differences
   - Do same for reasonable high value
2. If required, do minor recalibration
   - Final model recalibration will be refined
3. Use recalibrated sensitivity model to evaluate capture zones with RH Shaft off or on
4. Categorize sensitivities as per ASTM methodology using results of 1 and 3.

CATEGORIZATION OF SENSITIVITY TO CALIBRATION

Category	Mean Error Change from base case (ft)	PH Flux change from base case (MGD)
Insensitive (Insignificant)	ME change < 0.5	Flux change < 2
Slightly sensitive (Insignificant)	0.5 < ME change < 1.5	2 < Flux change < 4
Moderately sensitive (Significant)	1.5 < ME change < 2.5	4 < Flux change < 6
Highly sensitive (Significant)	ME change > 2.5	Flux change > 8

CATEGORIZATION OF SENSITIVITY TO SIMULATION OBJECTIVES

- Qualitative evaluation of particle tracking capture zones
  - Direction
  - Width of capture zone
  - Distance between time markers
- At focus area wells
  - Moanalua well
  - Halawa Shaft
  - Red Hill Shaft
  - Forward tracking from water table beneath Red Hill Storage Facility tanks
- For conditions of
  - Halawa Shaft and Red Hill Shaft pumping at maximum capacity
  - Halawa Shaft pumping at maximum capacity and Red Hill Shaft off

CATEGORIZATION OF SENSITIVITY TO SIMULATION OBJECTIVES (CONTINUED)

Category	Remarks
Insensitive (Insignificant)	No visible change in capture width or direction from base case
Slightly sensitive (Insignificant)	Visually noticeable change in capture width or direction
Highly sensitive (Significant)	Visually significant change in capture width or direction; Also evaluated estimates of change in width of capture at Halawa Shaft is greater than 1,000 feet

ASTM GUIDELINES FOR CATEGORIZATION OF SENSITIVITY SIMULATIONS

ASTM Category	Change in Calibration	Change in Conclusion	Remarks
Type I	Insignificant	Insignificant	Not of concern because regardless of input because conclusion remains the same
Type II	Significant	Insignificant	Not of concern because regardless of input because conclusion remains the same
Type III	Significant	Significant	Not of concern in traditional sensitivity analysis because calibration eliminates unreasonable values
Type IV	Insignificant	Significant	Requires additional data collection or evaluations to narrow data range or evaluate impact

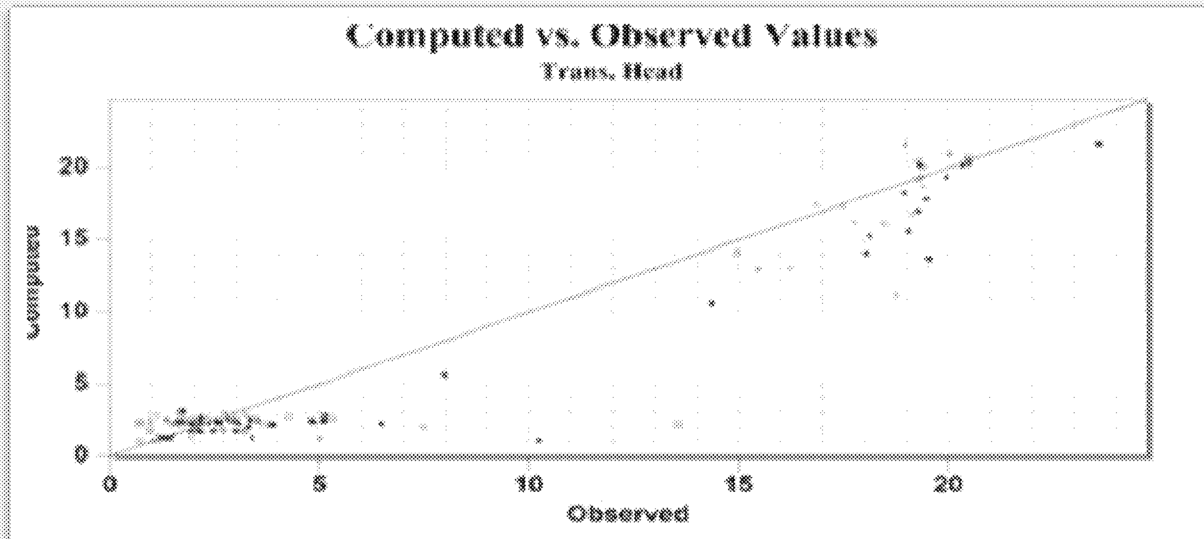
SENSITIVITY TO VERTICAL HYDRAULIC CONDUCTIVITY OF BASALT

SENSITIVITY TO VERTICAL HYDRAULIC CONDUCTIVITY OF BASALT PARAMETER CHANGE

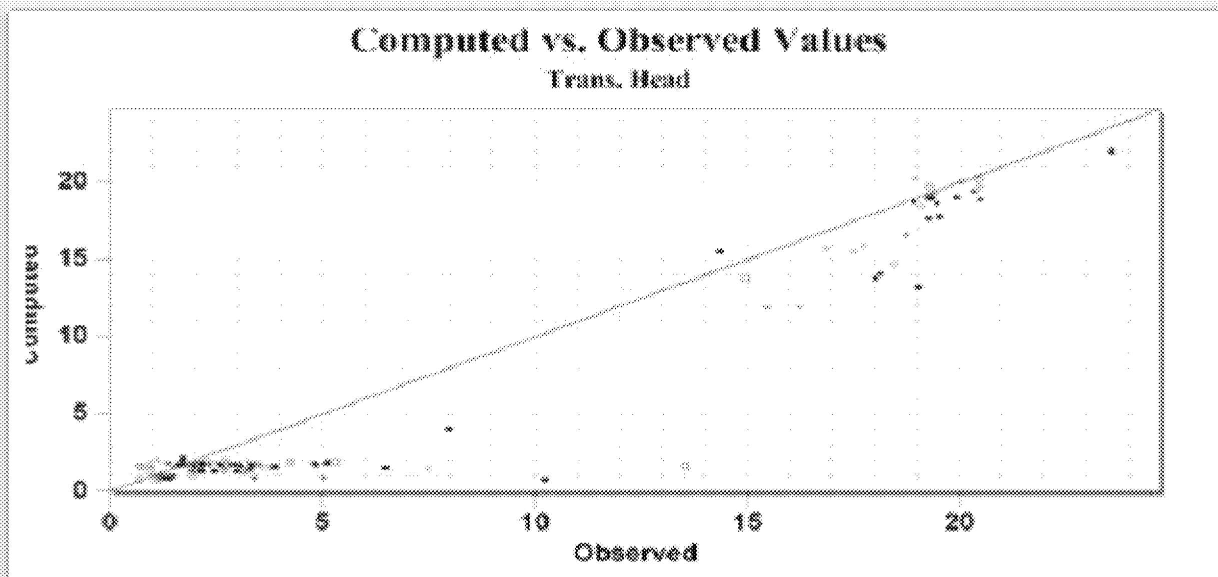
Basalt	Kv (ft/d)
Base	20
K (x 10)	200
K (x 0.1)	2

SENSITIVITY OF VERTICAL HYDRAULIC CONDUCTIVITY OF BASALT SCATTER PLOTS - 2017

Kv (x10)



Kv (x0.1)



SENSITIVITY TO VERTICAL HYDRAULIC CONDUCTIVITY OF BASALT SIMULATION STATISTICS SUMMARY

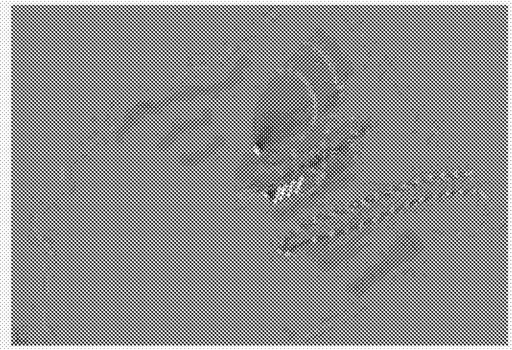
			Pearl Harbor Spring at Kalauao flux (MGD)			Kalauao Spring flux (MGD)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Original: Basalt Kv = 20 ft/d	-0.25	1.23	10.90	9.42	11.33	0.12	0.10	0.12
Basalt Kv – Low (K = 2 ft/d)								
Sensitivity Analysis: Basalt Kv = 2 ft/d	-2.23	3.14	8.40	7.32	8.76	0.17	0.15	0.17
Sensitivity Analysis: Basalt Kv = 2 ft/d + Caprock Kv = 0.12 (original = 0.08) + PH drain in Layers 2 & 3	1.26	2.67	7.38	6.12	7.82	0.07	0.06	0.07
Basalt Kv – High (K = 200 ft/d)								
Sensitivity Analysis: Basalt Kv = 200 ft/d	0.92	1.37	12.60	10.87	13.09	0.07	0.06	0.07
Sensitivity Analysis: Basalt Kv = 200 ft/d + Caprock Kv = 0.06 (orig = 0.08) + PH drain conductance = 200,000 (original = 2,000,000)	0.21	1.02	14.70	12.95	15.19	0.09	0.08	0.09

Key observations

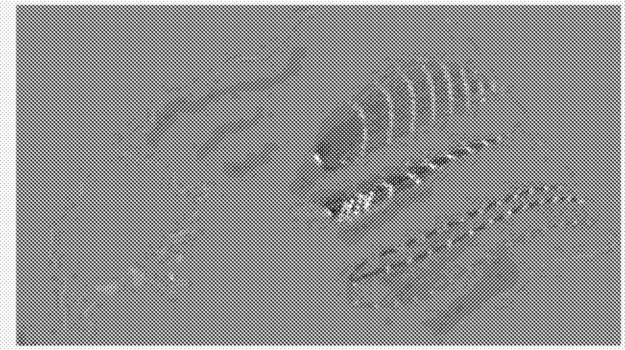
- Calibration statistics are moderately sensitive to Kv of basalt
- Sensitivity is higher to lowering Kv of basalt than to raising Kv of basalt
- Drain fluxes are slightly sensitive

VERTICAL HYDRAULIC CONDUCTIVITY OF BASALT RED HILL SHAFT ON

Base Case



Basalt Kv (x0.1)



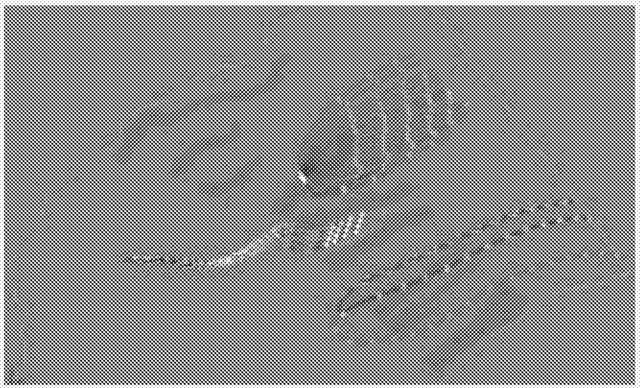
Basalt Kv (x10)

Arrows are 1-year time interval markers

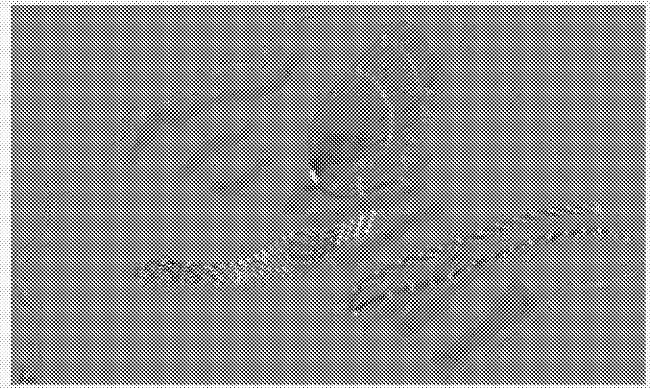
Key Observations

- Predictions are highly sensitive to Kv of basalt
- Capture zone for Halawa Shaft is more to the west for lower Kv and to the east for higher Kv
- Capture zone width of Red Hill Shaft is insensitive
- Tracking distances are larger with lower Kv of basalt
- Capture zone width for Halawa Shaft:
  - Base case = ~ 7,980 ft
  - Kv (x 0.1) = ~ 10,890 ft
  - Kv (x 10) = ~ 5,381 ft
- Red Hill Shaft captures water traveling beneath Red Hill Storage Facility

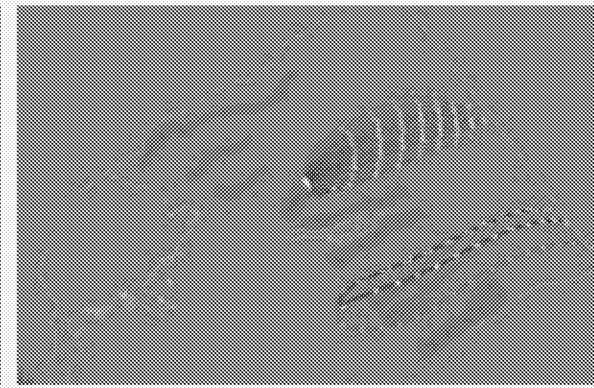
VERTICAL HYDRAULIC CONDUCTIVITY OF BASALT RED HILL SHAFT OFF



Base Case



Basalt Kv (x0.1)



Basalt Kv (x10)

Arrows are 1-year time interval markers

Key Observations

- Predictions are highly sensitive to Kv of basalt
- Tracking distances are larger with lower Kv of basalt
- Capture zone width for Halawa Shaft:
  - Base case = ~ 7980 ft
  - Kv (x 0.1) = ~ 11649 ft
  - Kv (x 10) = ~ 5700 ft
- Halawa Shaft does not intersect water that flows beneath Red Hill Storage Facility
- Sensitive to calibration and to conclusion = Type III

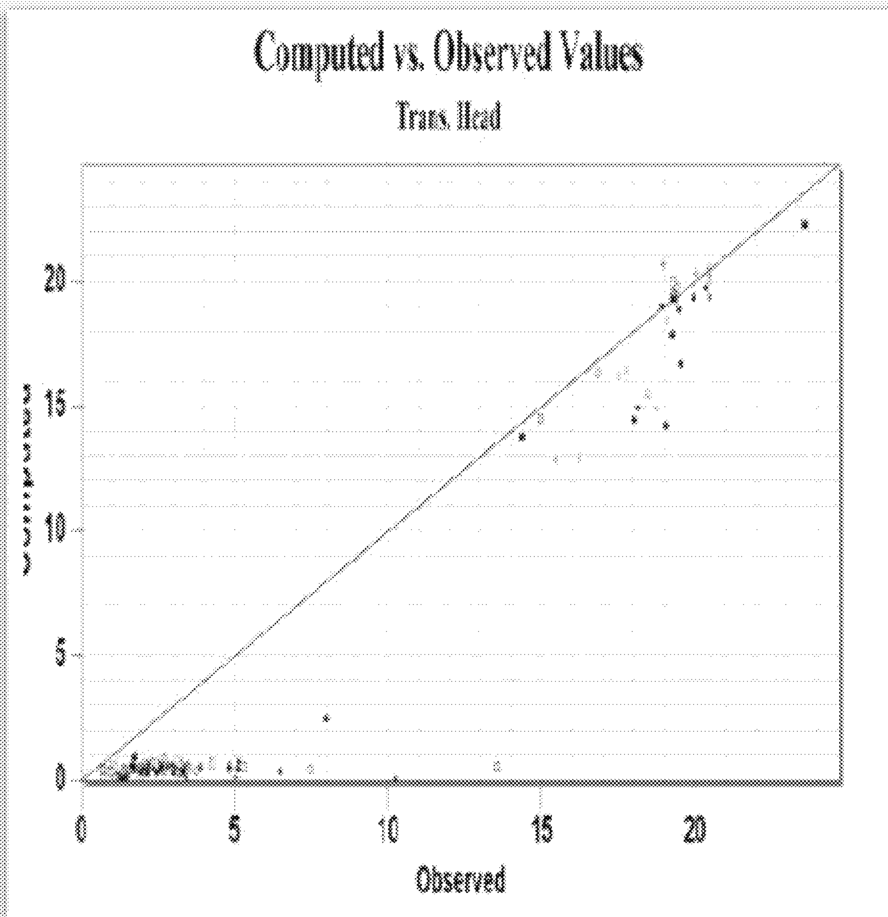
SENSITIVITY TO CONDUCTANCE OF OFFSHORE GENERAL HEAD BOUNDARIES

SENSITIVITY TO CONDUCTANCE OF OFFSHORE GENERAL HEAD BOUNDARIES

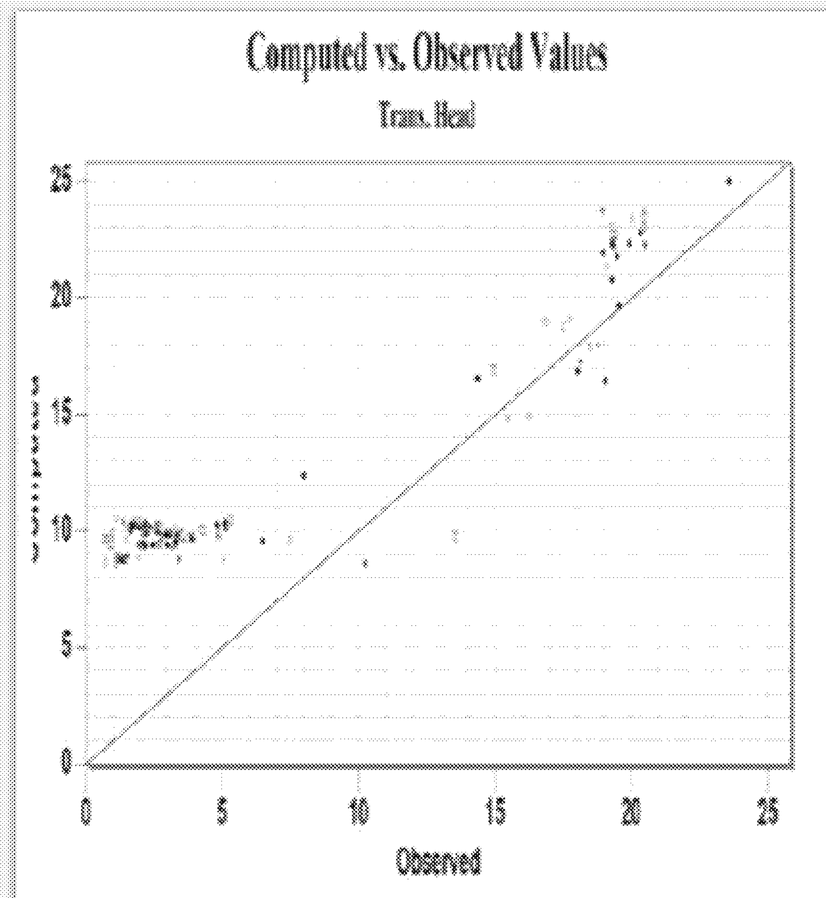
GHB conductance	Pearl Harbor (1/d)	Offshore (1/d)
Base C	0.005	0.014
C (x 10)	0.05	0.14
C (x 0.1)	0.0005	0.0014

SENSITIVITY TO CONDUCTANCE OF OFFSHORE GENERAL HEAD BOUNDARIES - 2017

C (x10)



C (x0.1)



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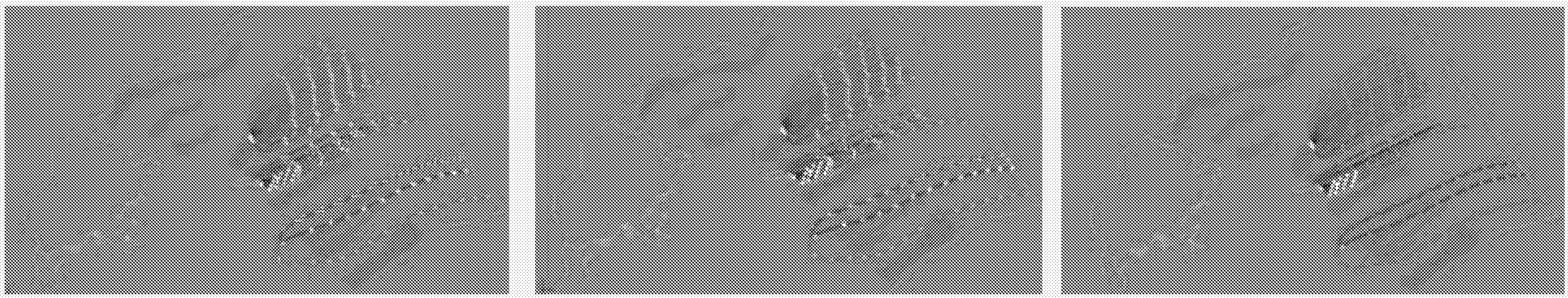
SENSITIVITY TO CONDUCTANCE OF OFFSHORE GENERAL HEAD BOUNDARIES – SIMULATION STATISTICS SUMMARY

			Pearl Harbor Spring at Kalauao Flux (MGD)			Kalauao Spring Flux (MGD)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Original: GHB = 0.005 and 0.01375 (ft2/d)/(ft2)	-0.25	1.23	10.9	9.4	11.3	0.12	0.10	0.12
Sensitivity Analysis: GHB =0.0005 and 0.001375 (ft2/d)/(ft2)	-2.62	2.88	17.4	15.3	17.4	0.18	0.16	0.18
Sensitivity Analysis: GHB =0.05 and 0.1375 (ft2/d)/(ft2)	0.32	1.25	9.5	8.1	10.0	0.10	0.09	0.11

Key observations

- Calibration statistics and PH Spring fluxes are highly sensitive to lowering the GHB conductance but insensitive to raising GHB conductance
- Water levels in caprock are out of calibration when offshore GHBs are lowered or raised

CONDUCTANCE OF OFFSHORE GENERAL HEAD BOUNDARIES – RED HILL SHAFT ON



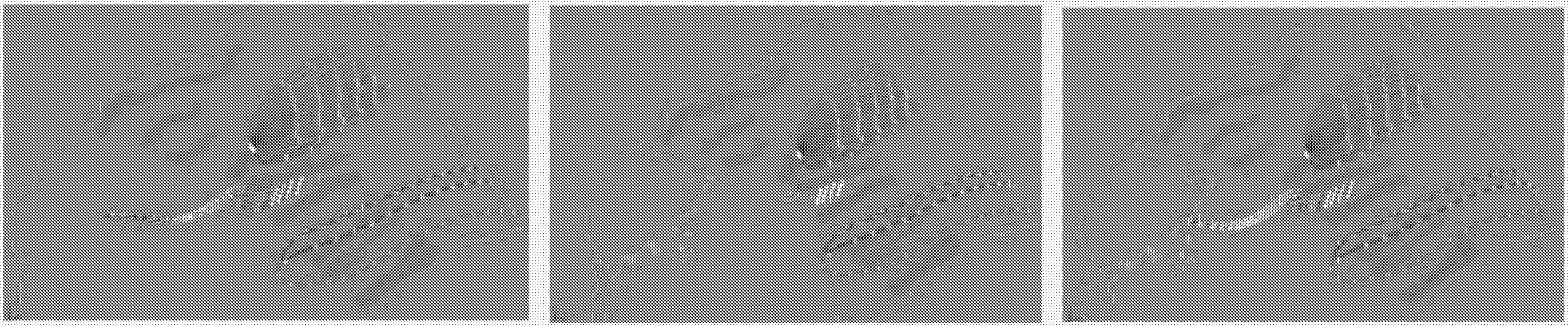
Base Case GHB C (x0.1) GHB C (x10)

Arrows are 1-year time interval markers

Key Observations

- Predictions are insensitive to offshore GHB conductance

CONDUCTANCE OF OFFSHORE GENERAL HEAD BOUNDARIES – RED HILL SHAFT OFF



Base Case GHB C (x0.1) GHB C (x10)

Arrows are 1-year time interval markers

Key Observations

- Predictions are insensitive to offshore GHB conductance
- Capture zone for Halawa Shaft is of same width
- Forward track particles from Red Hill area are of same pattern
- Sensitive or insensitive to calibration but insensitive to prediction = Type II or Type I

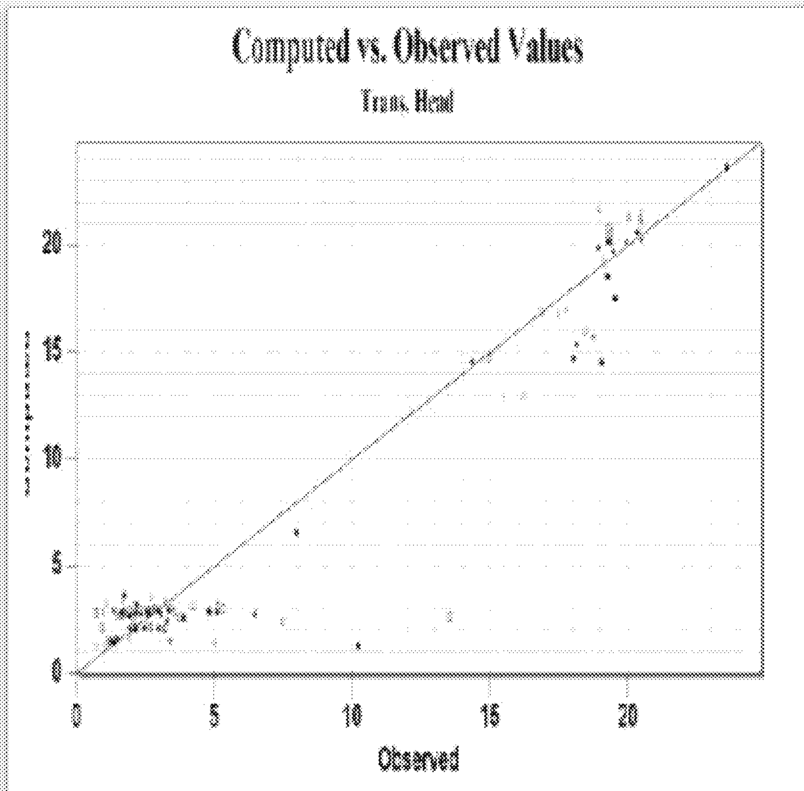
SENSITIVITY TO RECHARGE

SENSITIVITY TO RECHARGE PARAMETER CHANGE

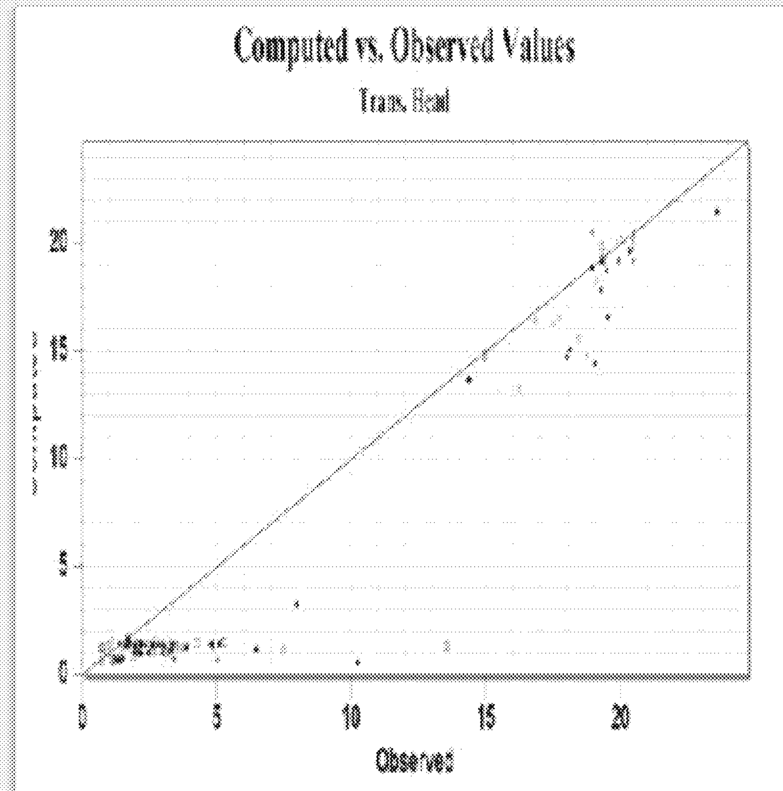
Recharge (MGD)	2006	2015	2017
Base	48.04	35.81	36.77
R (x 1.2)	57.65	42.97	44.12
R (x 0.8)	40.03	29.84	30.64

SENSITIVITY TO AREAL RECHARGE SCATTER PLOTS - 2017

Kv (x10)



Kv (x0.1)



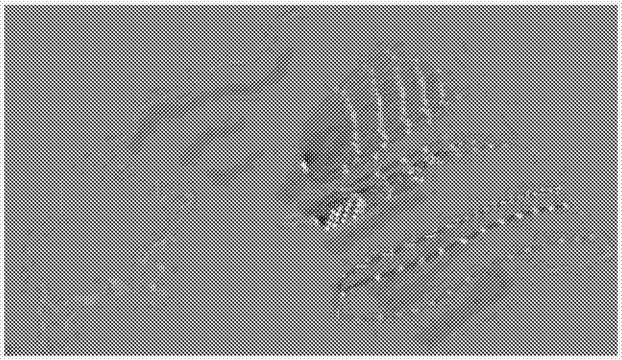
SENSITIVITY TO AREAL RECHARGE SIMULATION STATISTICS SUMMARY

			Pearl Harbor Spring at Kalauao Flux (MGD)			Kalauao Spring Flux (MGD)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Original: Recharge (ft/d): SP1=x1.27; SP2=x0.95; SP3 = x0.97	-0.25	1.23	10.9	9.4	11.3	0.12	0.10	0.12
Sensitivity Analysis: Recharge (ft/d): SP1 = x1.02; SP2 = x0.76; SP3 = x0.78	2.53	2.79	5.2	5.1	7.0	0.06	0.06	0.08
Sensitivity Analysis: Recharge = <20% + Caprock Kv = 0.04 (orig = 0.08)	0.79	1.40	9.5	9.5	11.4	0.10	0.10	0.12
Sensitivity Analysis: Recharge (ft/d): SP1 = x1.52; SP2 = x1.14; SP3 = x1.17	-2.98	3.27	16.6	13.7	15.7	0.17	0.15	0.17
Sensitivity Analysis: Recharge = >20% + Caprock Kv = 0.14 (orig = 0.08)	-0.80	1.57	11.0	8.4	10.2	0.12	0.10	0.11

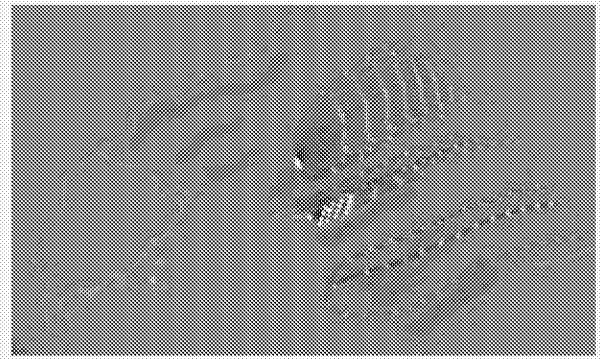
Key observations

- Calibration statistics are highly sensitive to 20% change in recharge
- Pearl Harbor Spring fluxes are moderately sensitive

SENSITIVITY TO AREAL RECHARGE – RED HILL SHAFT ON



Base Case



R (x 0.8)

R (x 1.2)

Arrows are 1-year time interval markers

Key Observations

- Predictions are insensitive to Recharge

SENSITIVITY TO AREAL RECHARGE – RED HILL SHAFT OFF

Base Case R (x 0.8) R (x 1.2)

Arrows are 1-year time interval markers

Key Observations

- Predictions are slightly sensitive to Recharge
- Higher recharge has narrower capture zone
- Sensitive to calibration but insensitive to prediction = Type II

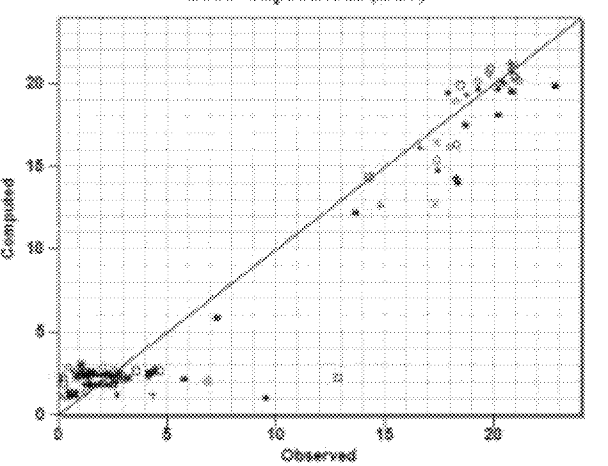
SENSITIVITY TO SAPROLITE HYDRAULIC CONDUCTIVITY

SENSITIVITY TO SAPROLITE HYDRAULIC CONDUCTIVITY PARAMETER CHANGE

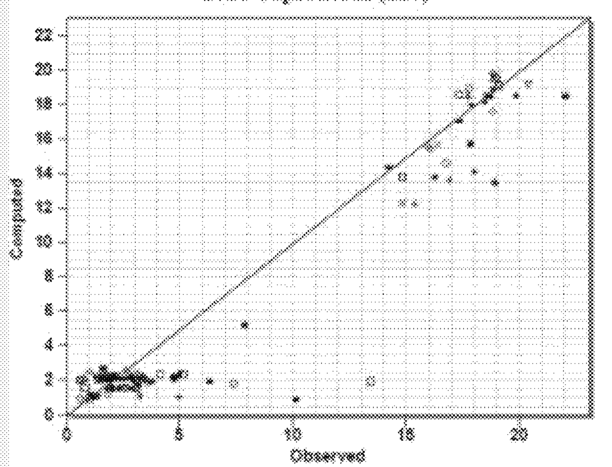
	Saprolite Layer 2		Saprolite Layer 3	
	Kh	Kv	Kh	Kv
Base	0.1	0.01	10	1
K (x 10)	1	0.1	100	10
K (x 0.1)	0.01	0.001	1	0.1

SENSITIVITY OF SAPROLITE HYDRAULIC CONDUCTIVITY SCATTER PLOTS

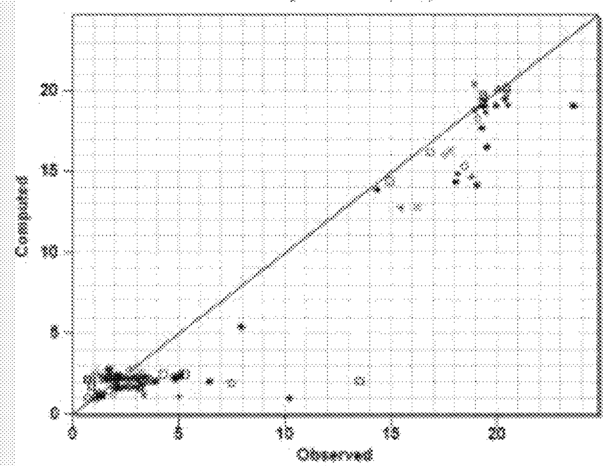
2006 Saprolite K (x 10)



2015 Saprolite K (x10)

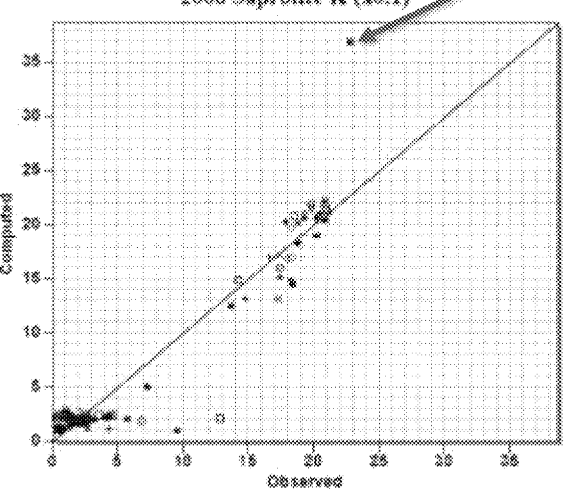


2017 Saprolite K (x10)

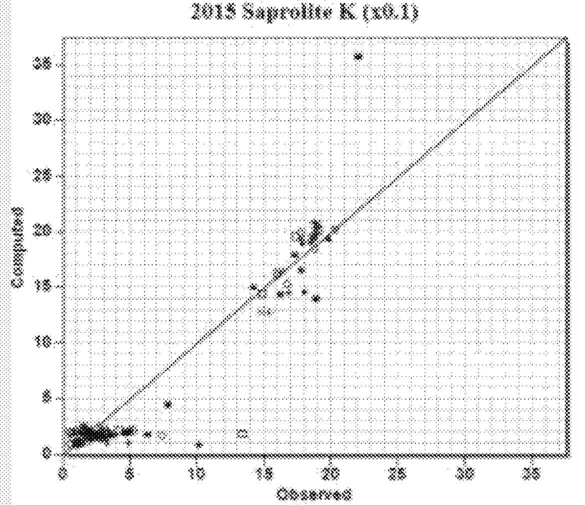


RHMW07

2006 Saprolite K (x0.1)

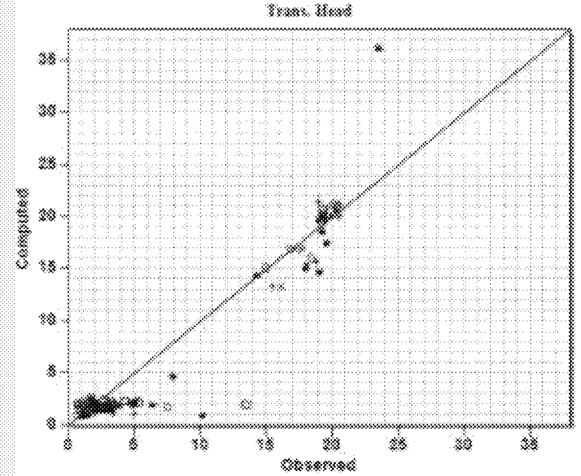


2015 Saprolite K (x0.1)



2017 Saprolite K (x0.1)

Trans. Head



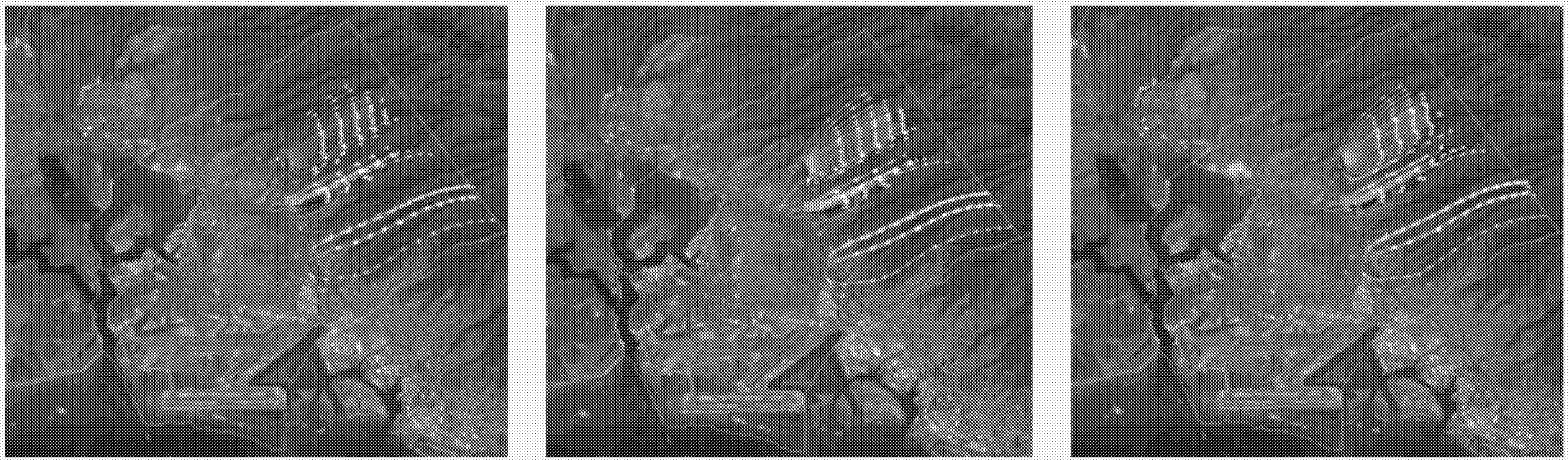
SENSITIVITY TO SAPROLITE HYDRAULIC CONDUCTIVITY SIMULATION STATISTICS SUMMARY

			Pearl Harbor Spring at Kalauao flux (MGD)			Kalauao Spring flux (MGD)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Original: Saprolite K	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Saprolite K (x 10)	0.72	1.59	9.50	8.06	9.93	0.10	0.09	0.11
Saprolite K (x 0.1)	-0.59	3.05	11.06	9.64	11.55	0.12	0.11	0.12

Key observations

- Calibration statistics are slightly sensitive to saprolite K
- Drain fluxes are insensitive to saprolite K

SAPROLITE HYDRAULIC CONDUCTIVITY RED HILL SHAFT ON



Base Case

Saprolite K (x0.1)

Saprolite K (x10)

Key Observations

- Predictions are insensitive to Saprolite K
- Capture zone for Halawa Shaft is of same width
- Capture zone of Red Hill Shaft is of same width
- Tracking distances are similar to base case
- Red Hill Shaft captures water traveling beneath Red Hill Storage Facility

Arrows are 1-year time interval markers

Pathline colors

Layer 1

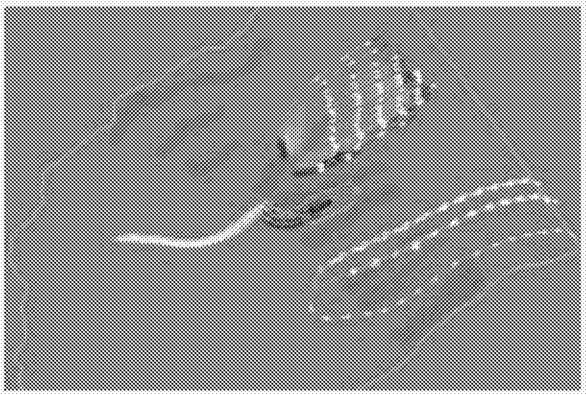
Layer 2

Layer 3

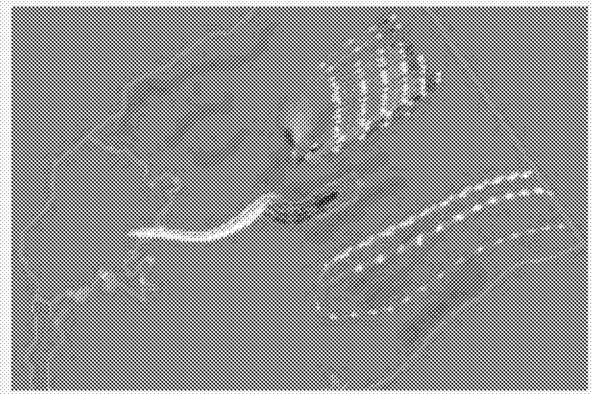
Layer 4

Layer 5

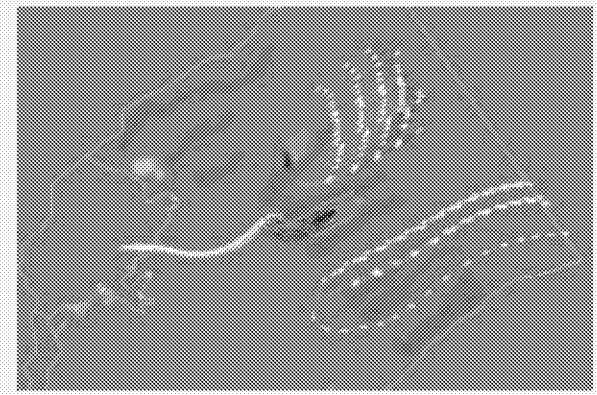
SAPROLITE HYDRAULIC CONDUCTIVITY RED HILL SHAFT OFF



Base Case



Saprolite K (x0.1)



Saprolite K (x10)

Arrows are 1-year time interval markers

Pathline colors

Layer 1
Layer 2
Layer 3
Layer 4
Layer 5

Key Observations

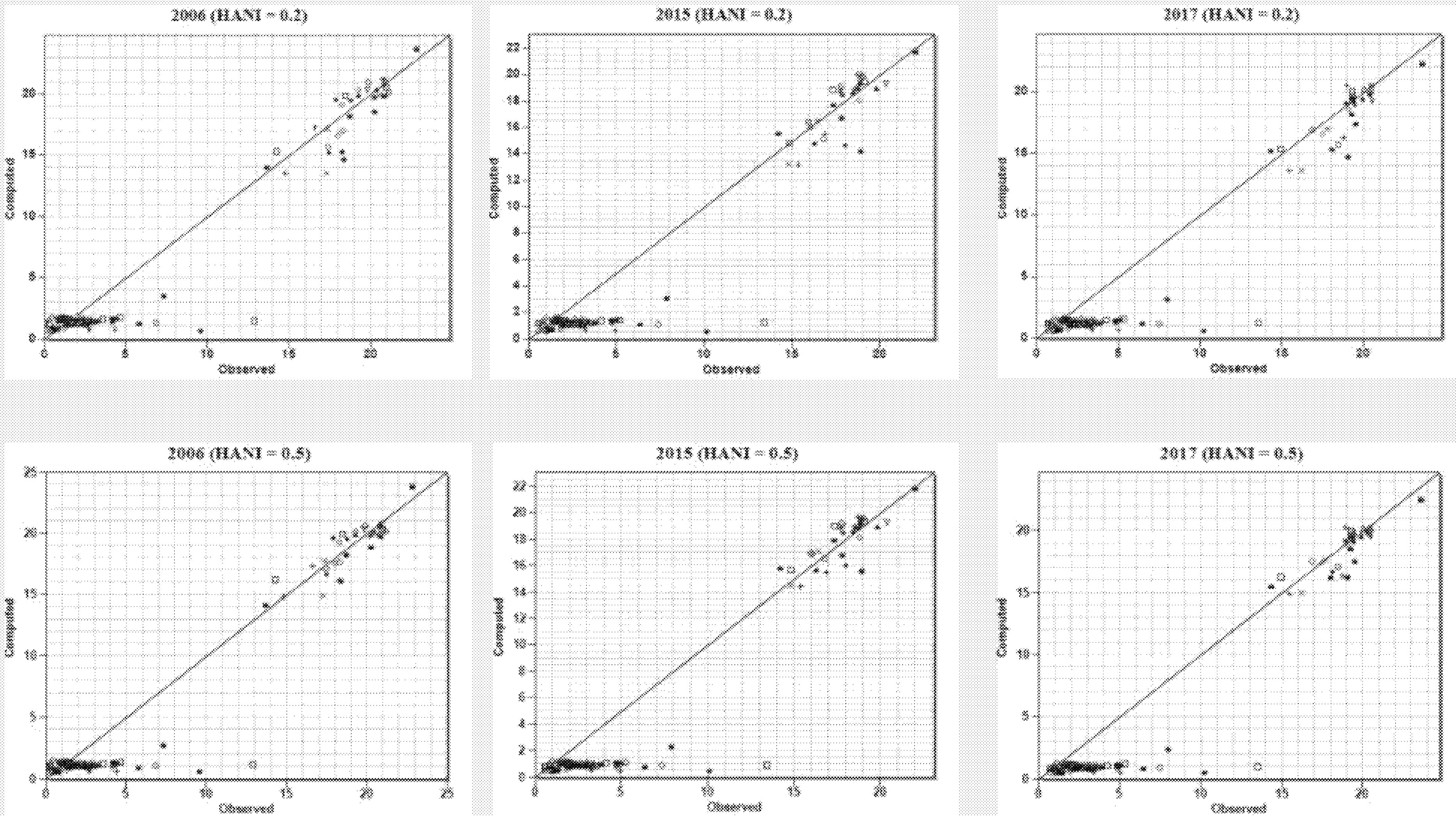
- Predictions are insensitive to Saprolite K
- Capture zone for Halawa Shaft is of same width
- Forward track particles from Red Hill area are of same pattern
- Insensitive to calibration and to conclusion = Type I

SENSITIVITY TO BASALT HORIZONTAL ANISOTROPY

SENSITIVITY TO BASALT HORIZONTAL ANISOTROPY PARAMETER CHANGE

	HANI
Base	0.33
HANI (lower)	0.2
HANI (higher)	0.5

SENSITIVITY OF BASALT HORIZONTAL ANISOTROPY SCATTER PLOTS



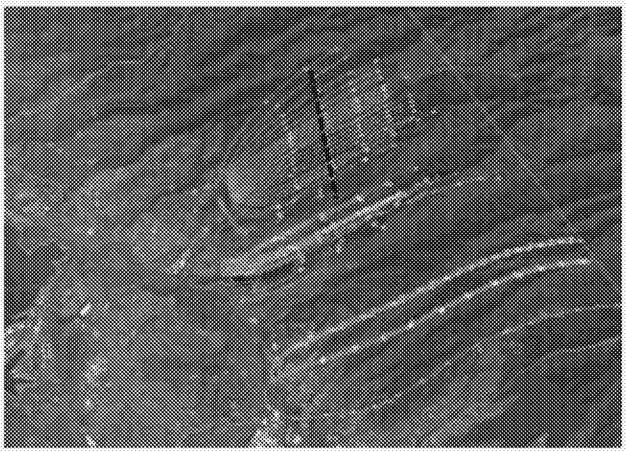
SENSITIVITY OF BASALT HORIZONTAL ANISOTROPY (HANI)

			Pearl Harbor Spring at Kalauao flux (MGD)			Kalauao Spring flux (MGD)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Original: Basalt HANI = 0.33	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Sensitivity analysis: HANI = 0.2	-2.9	3.25	9.3	8	9.8	0.1	0.1	0.1
Sensitivity analysis: HANI = 0.2, +caprock Kv=0.03 ft/d, +basalt Kh=4293 ft/d	0.13	0.99	18.18	16.40	18.62	0.14	0.12	0.14
Sensitivity analysis: HANI = 0.5	1.41	1.78	11.95	10.3	12.3	0.11	0.1	0.11
Sensitivity analysis: HANI = 0.5, +caprock Kv=0.01 ft/d, +basalt Kh=2632 ft/d	-0.13	0.99	22.46	20.51	22.84	0.17	0.15	0.17

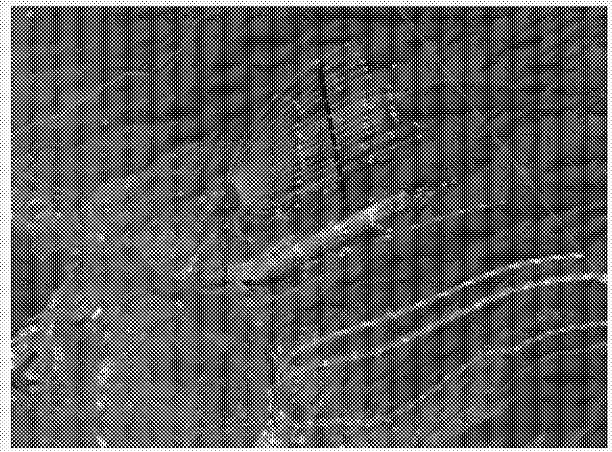
Key observations

- Calibration statistics are moderately sensitive to basalt HANI
- Drain fluxes are insensitive to basalt HANI

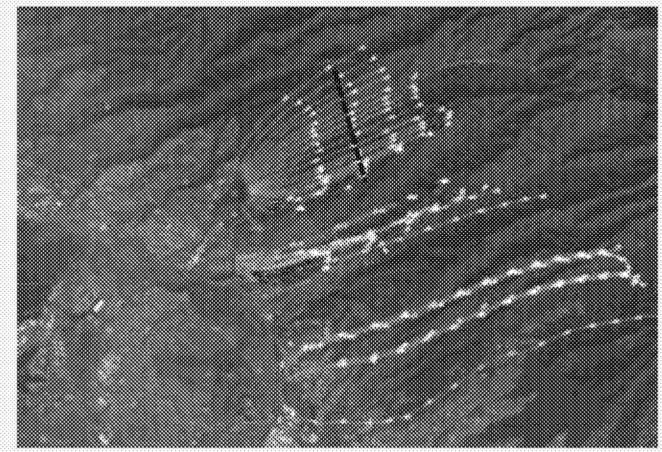
SENSITIVITY OF BASALT HORIZONTAL ANISOTROPY RED HILL SHAFT ON



Base Case



Basalt HANI = 0.2



Basalt HANI = 0.5

Key Observations

- Prediction is slightly sensitive to basalt horizontal anisotropy
- Capture zones are slightly to the west with HANI=0.2
- Capture zones are slightly to the east with HANI=0.5
- Capture zone width for Halawa Shaft:
  - Base HANI=0.33 (~ 7980 ft)
  - HANI=0.2 (~ 8380 ft)
  - HANI=0.5 (~ 7350 ft)
- Red Hill Shaft captures water originating from the water table beneath Red Hill Storage Facility footprint

Arrows are 1-year time interval markers

Pathline colors

Layer 1

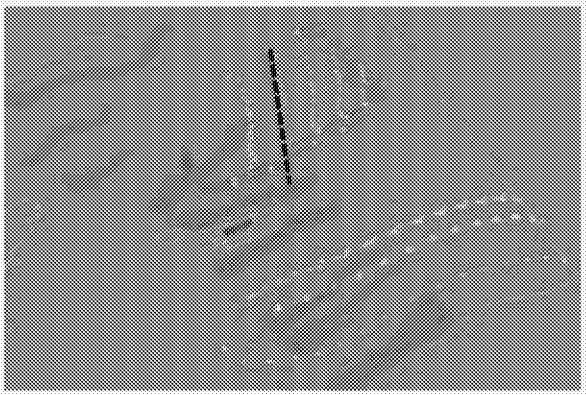
Layer 2

Layer 3

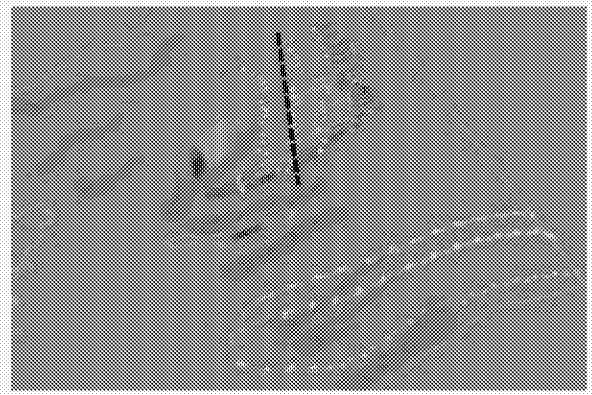
Layer 4

Layer 5

SENSITIVITY OF BASALT HORIZONTAL ANISOTROPY RED HILL SHAFT OFF



Base Case



Basalt HANI = 0.2

Basalt HANI = 0.5

Arrows are 1-year time interval markers

Pathline colors

Layer 1

Layer 2

Layer 3

Layer 4

Layer 5

Key Observation

- Prediction is slightly sensitive to basalt horizontal anisotropy
- Capture zone width for Halawa Shaft (dashed blue lines):
  - Base HANI=0.33 (~ 8450 ft)
  - HANI=0.2 (~ 9080 ft)
  - HANI=0.5 (~ 7950 ft)
- Halawa Shaft does not capture water originating from underneath Red Hill Storage Facility
- Sensitive to calibration but insensitive to prediction = Type II

SENSITIVITY TO NE FLUX

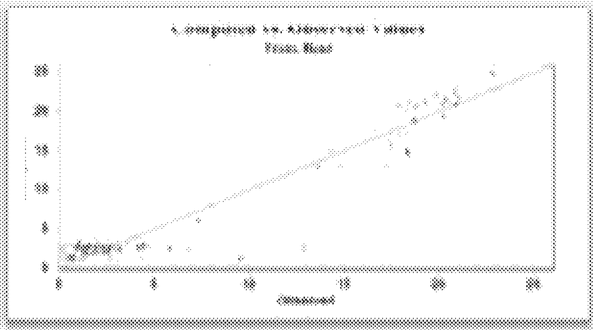
SENSITIVITY TO NE FLUX PARAMETER CHANGE

NE Flux (MGD)	
Base	22.4
F (x 1.2)	26.88
F (x 0.8)	17.9

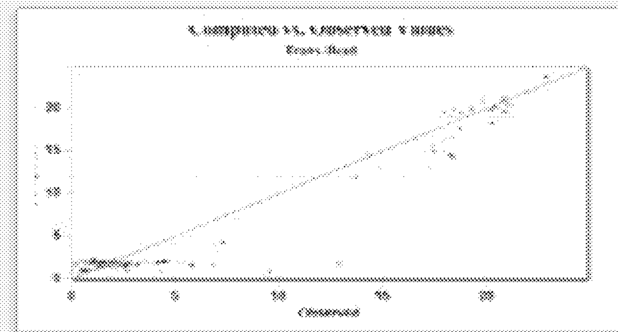
SENSITIVITY TO NE FLUX SCATTER PLOTS

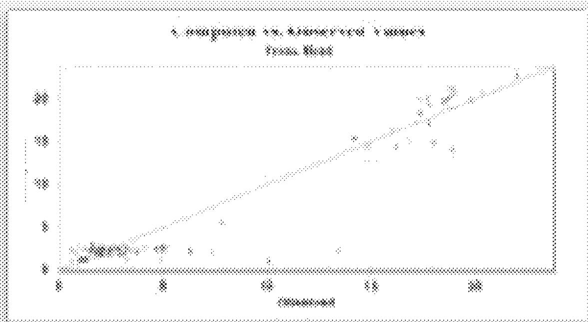
F (x 1.2)

F (x 0.8)

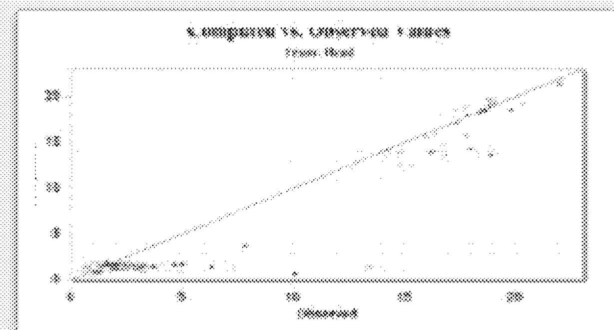


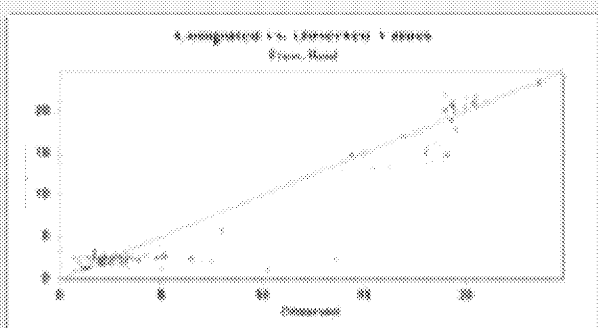
2006



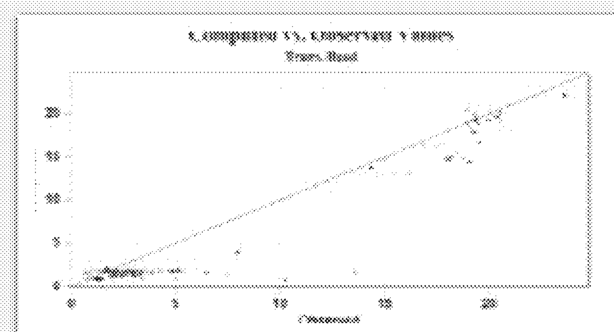


2015





2017



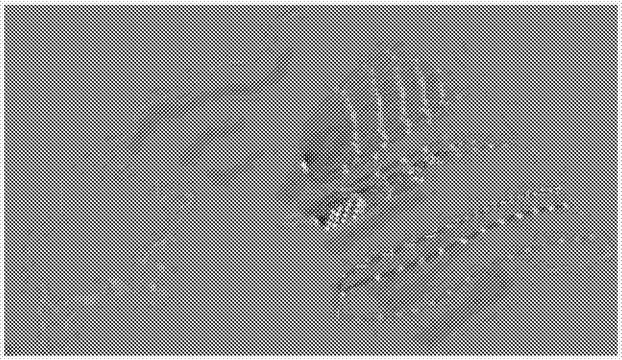
SENSITIVITY TO NE FLUX SIMULATION STATISTICS SUMMARY

	ME (ft)	RMS (ft)	Pearl Harbor Spring at Kalauao Flux (MGD) 2006	2015	2017	Kalauao Spring Flux (MGD) 2006	2015	2017
Original: NE Flux = 22.4 MGD	-0.25	1.23	10.9	9.4	11.3	0.12	0.10	0.12
Sensitivity Analysis: NE Flux (* 0.8)	1.50	1.92	7.9	6.4	8.4	0.09	0.07	0.09
Sensitivity Analysis: NE Flux (* 0.8) Caprock Kv = 0.055 (orig = 0.08)	0.45	1.27	10.6	9.0	11.0	0.11	0.10	0.12
Sensitivity Analysis: NE Flux (* 1.2)	-1.98	2.32	13.8	12.4	14.3	0.15	0.13	0.15
Sensitivity Analysis: NE Flux (* 1.2) + Caprock Kv = 0.11 (orig = 0.08)	-0.81	1.46	10.9	9.5	11.3	0.12	0.11	0.12

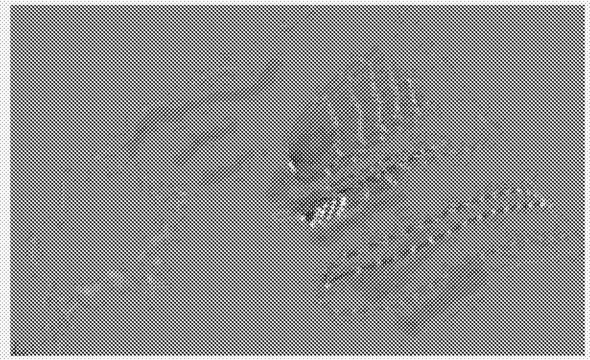
Key observations

- Calibration statistics are moderately sensitive to 20% change in NE flux
- PH Spring fluxes are slightly sensitive to 20% change in NE flux

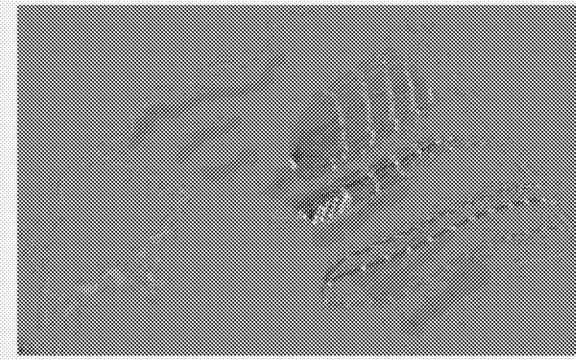
SENSITIVITY TO NE FLUX – RED HILL SHAFT ON



Base Case



F (x 0.8)



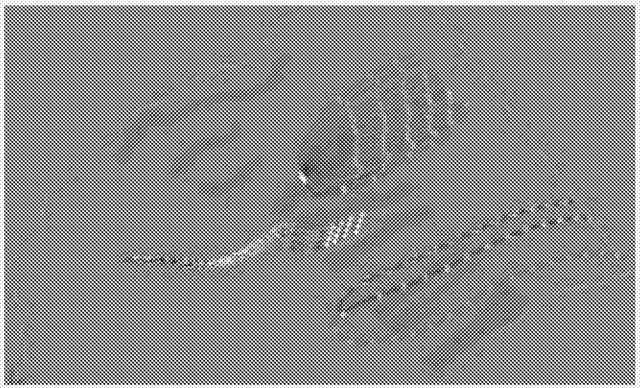
F (x 1.2)

Key Observations

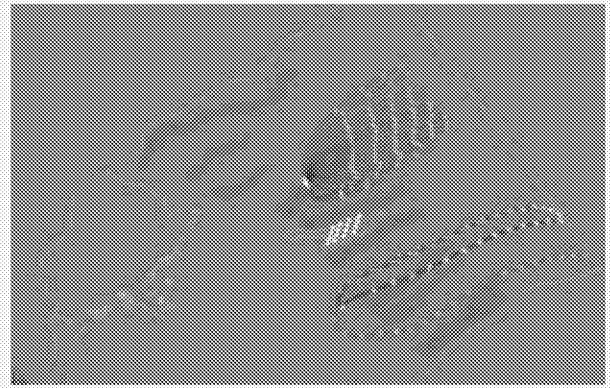
- Predictions are insensitive to NE flux
- Capture zone at Halawa Shaft is slightly (less than 50 feet) smaller for larger NE flux and slightly (less than 50 feet) larger for smaller NE flux
- Water originating from the water table under the Red Hill Storage Facility footprint is captured by Red Hill Shaft

Arrows are 1-year time interval markers

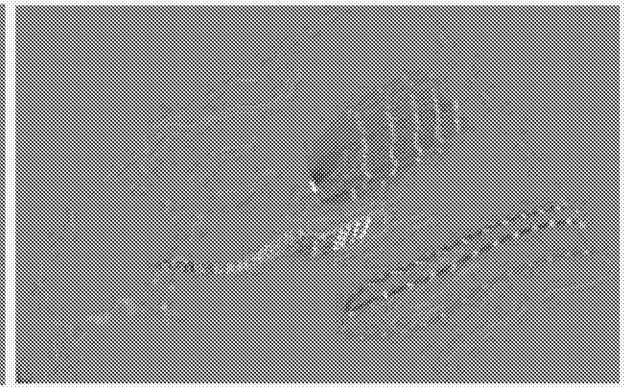
SENSITIVITY TO NE FLUX – RED HILL SHAFT OFF



Base Case



F (x 0.8)



F(x 1.2)

Arrows are 1-year time interval markers

Key Observations

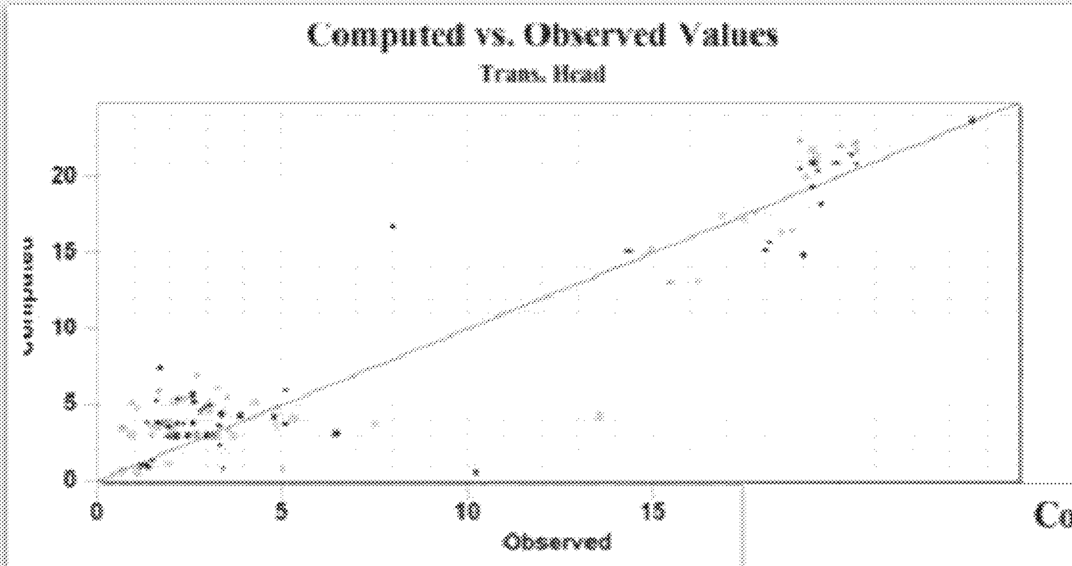
- Predictions are insensitive to NE flux
- Capture zone at Halawa Shaft is slightly (less than 50 feet) smaller for larger NE flux and slightly (less than 50 feet) larger for smaller NE flux
- Capture zone of Halawa Shaft does not capture water originating from the water table under the Red Hill Storage Facility tanks
- Sensitive or insensitive to calibration but insensitive to prediction = Type II or Type I

SENSITIVITY TO HORIZONTAL HYDRAULIC CONDUCTIVITY OF CAPROCK

SENSITIVITY TO KH OF CAPROCK – PARAMETER CHANGE

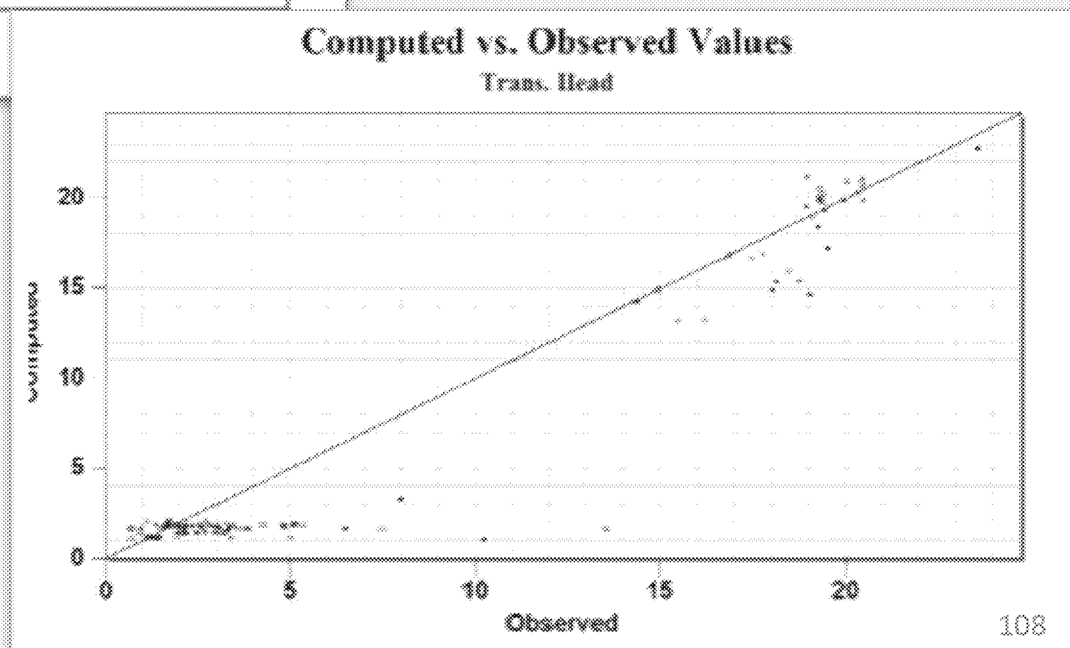
Caprock Kh (ft/d)	
Base	1,204
Low Kh	100
High Kh	2,400

SENSITIVITY TO TO KH OF CAPROCK
2017 SCATTER PLOTS



Low Kh

High Kh



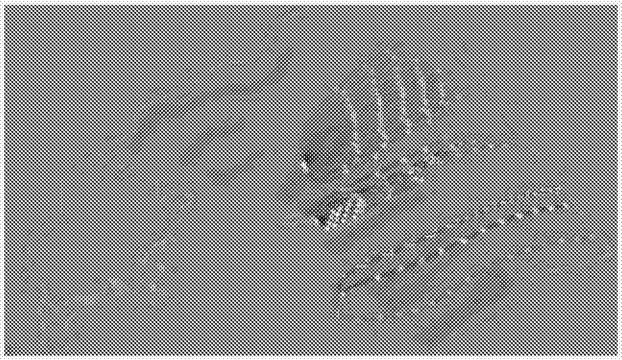
SENSITIVITY TO KH OF CAPROCK SIMULATION STATISTICS SUMMARY

			Pearl Harbor Spring at Kalauao Flux (MGD)			Kalauao Spring Flux (MGD)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Original: Caprock Kh = 1208 (ft/d)	-0.25	1.23	10.9	9.4	11.3	0.12	0.10	0.12
Sensitivity Analysis: Caprock Kh = 100 (ft/d)	-2.67	2.93	15.7	13.8	15.8	0.17	0.15	0.17
Sensitivity Analysis: Caprock Kh = 100 ft/d + Caprock Kv = 0.18 (orig = 0.08)	-1.23	1.74	11.1	9.3	11.2	0.12	0.11	0.13
Sensitivity Analysis: Caprock Kh = 2400 (ft/d)	0.06	1.20	10.3	8.9	10.8	0.11	0.10	0.12
Sensitivity Analysis: Caprock Kh = 2400 ft/d + Caprock Kv = 0.075 (orig = 0.08)	-0.17	1.21	10.9	9.4	11.3	0.12	0.10	0.12

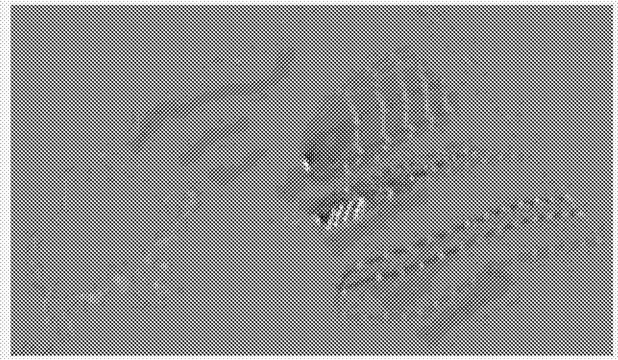
Key observations

- Calibration statistics are highly sensitive to lowering the Kh of caprock but insensitive to raising the Kh of caprock

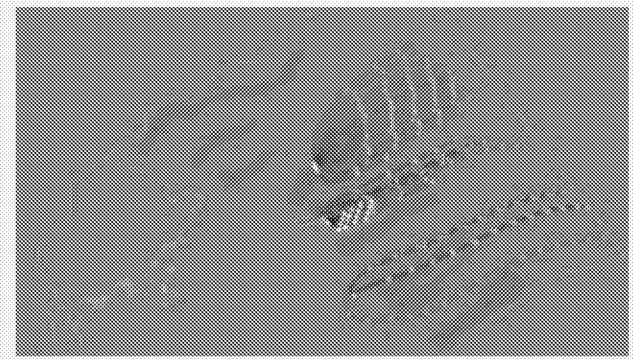
SENSITIVITY TO KH OF CAPROCK – RED HILL SHAFT ON



Base Case



Low Kh



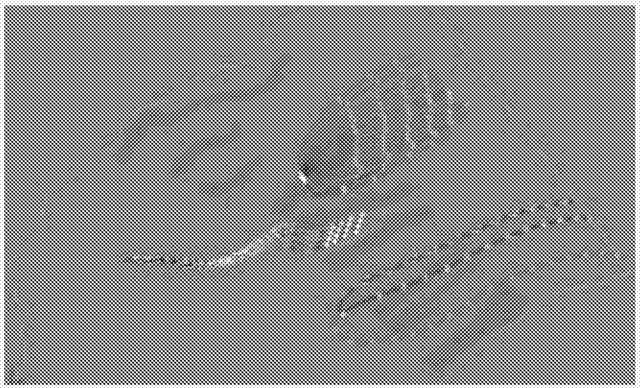
High Kh

Arrows are 1-year time interval markers

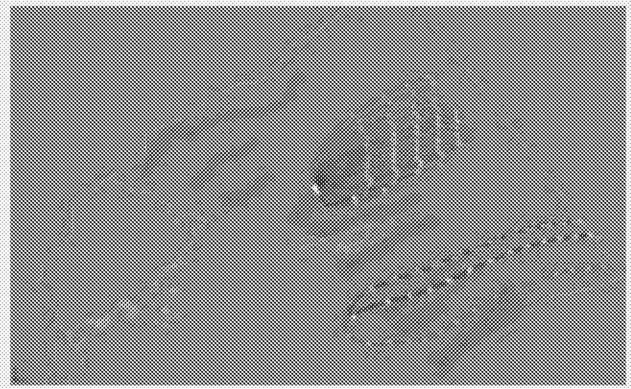
Key Observations

- Predictions are insensitive to Kh of Caprock

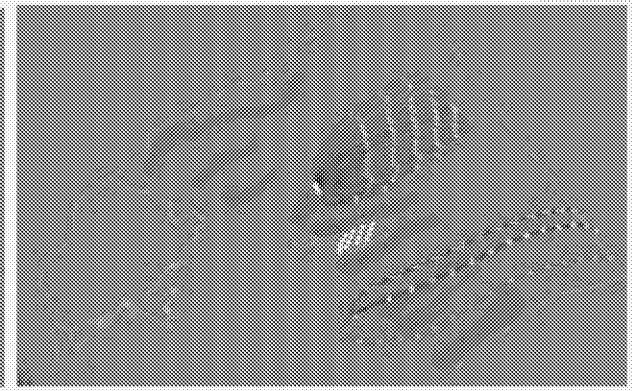
SENSITIVITY TO KH OF CAPROCK – RED HILL SHAFT OFF



Base Case



Low Kh



High Kh

Arrows are 1-year time interval markers

Key Observations

- Predictions are insensitive to Kh of Caprock
- Sensitive / Insensitive to calibration and insensitive to prediction = Type II or I

SUMMARY OF SENSITIVITY SIMULATIONS

Parameter	Base Case	Low	High	Water level difference between RHMW06 and Halawa Shaft *	Sensitivity to calibration	Sensitivity to conclusions	ASTM Sensitivity Type
Saprolite hydraulic conductivity	(* 1.0)	(* 0.1)	(* 10)	4.94, 5.73, 5.29	Insensitive	Insensitive	I
Horizontal anisotropy of basalt	0.33	0.2	0.5	4.94, 7.00, 4.80	Moderate	Slight	II
Vertical hydraulic conductivity of basalt (ft/d)	20	2	200	4.94, 8.70, 3.49	Moderate	High	III
Horizontal hydraulic conductivity of caprock (ft/d)	1208	100	2400	4.94, 5.86, 5.67	High / Insensitive	Insensitive	I or II
GHB conductance for offshore boundaries	(* 1.0)	(* 0.1)	(* 10)	4.94, 5.79, 5.65	High / Low	Insensitive	I or II
NE boundary inflow	(* 1.0)	(* 0.8)	(* 1.2)	4.94, 5.58, 5.78	Moderate / Low	Insensitive	I or II
Recharge	(* 1.0)	(* 0.8)	(* 1.2)	4.94, 5.58, 5.76	High	Insensitive	II

* Larger positive value indicates larger simulated slope towards Halawa Shaft

STATUS OF CURRENT SYNOPTIC SURVEY

- Projected end date
- Projected date for release of raw data
- Projected date for release of final data

REVIEW OF ISSUES AND ACTION ITEMS

- All pertinent data have been requested
- Water pumping and quality data from Watercress Farms to cement plant
- Water quality data from BWS well on Red Hill

NEXT GWMWG MEETING

- **March 16, 2018: Full-day, in-person meeting**